TWR- 17748

Space Shuttle
Solid Rocket Motors
Morton Thiokol Inc

FINAL REPORT FOR STA-2A NDT TESTING

(NASA-CR-179301) STA-2A NDT TESTING Final Report (Morton Thiokol) 117 p CSCL 14D N88-18937

Unclas
G3/38 0128281

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

Contract No. NAS8-30490

DR. No. 5-3

WBS No. FN

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FORM TC 4677 (REV 6-83)

117

FINAL REPORT ON STA-2A NDT TESTING

25 NOVEMBER 1987

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1.0 INTRODUCTION

This test report describes the Nondestructive Testing (NDT) on the Space Shuttle Solid Rocket Booster (SRB) Filament wound Case (FWC) Short Stack Structural Test Article no. 2 (STA-2A) during test of phases 1B-9C.

The primary objective of this testing was to verify the structural integrity of the SRB-FWC for critical design loads. Another objective was to quantify the effects of load distributions in the Aft Skirt. The NDT objectives were to determine the Acoustic Emission characteristics of the FWC SRB and to identify possible design deficiencies or defect growth.

The tests occurred in building 4572 at Marshall Space Flight Center (MSFC) from 25 January to 2 August, 1985.

A brief description of each test phase follows:
PHASE 1B-ACOUSTIC EMISSION CYCLE: This test was performed to determine the AE characteristics of the FWC during pressure testing.

PHASE 2-AFT ET ATTACH POINT INFLUENCE TEST: This test was performed to determine the local deflections, strains, and stresses of the Aft SRM/ET Attach Ring Area during individual loading of struts, individual tangential and radial loads, and individual moment loads. Loading was performed with the STA at ambient temperature and pressure.

PHASE 3-AFT ET ATTACH POINT, INFLUENCE TEST WITH INTERNAL PRESSURE: This test was performed to determine deflections, strains, and stresses of the Aft SRM/ET Attach Ring Area during the tests.

PHASE 4-AFT ET ATTACH POINT, HIGH Q BOOST: This test was to determine deflections, strains, and stresses of the SRM/ET Attach Ring Area during High Q Boost.

PHASE 5-AFT ET ATTACH POINT, LIFT-OFF: This test was performed to determine deflections, strains and stresses of the Aft Skirt/ET Attach Ring Area during lift-off.

PHASE 6-FORWARD ET ATTACH POINT, INFLUENCE: This test was performed to determine the strain response of the FWC and the local deflections of the Forward FWC Segment during the tests.

PHASE 7-FORWARD ET ATTACH POINT LIFT-OFF: This test was performed to determine deflections, strains, and stresses during Lift-Off.

PHASE 8-FORWARD ET ATTACH POINT, MAXIMUM AXIAL ACCELERATION: This test was performed to determine deflections, strains, and stresses during maximum acceleration.

PHASE 9C-PRELAUNCH: This test was performed to determine deflections, strains, and stresses during prelaunch loads.

2.0 ACKNOWLEDGEMENTS

The Nondestructive Testing covered in this report was conducted in parallel with the Static Structural tests conducted by NASA at MSFC. The NDT is directly influenced by the test facility, test article, test loads and instrumentation. These subjects are covered in great detail by NASA reports, "FWC-QUAL-ET 86-011" and "SRB/FWC-QUAL-ET 86-012". Due to the importance of these factors, reproduction of sections of these reports pertinent to the NDT results are included in this report. Load ramps and drawings of test article or test facility are taken directly from these documents.

3.0 NDT INSPECTION METHODS

A brief description of the three NDT methods carried out on STA-2A follows.

3.1 Scanning Ultrasonic Testing and Recording Apparatus (SUTRA)

SUTRA operates in the Ultrasonic through transmission mode. In this mode ultrasonic pulses transmit from one transducer, through the composite, and are received by a second transducer on the other side of the test article. The computer records the net attenuation of the ultrasonic pulses as the scanning system moves the transducers. The main advantage of this inspection technique is a computer drawn attenuation map of the part is generated. The disadvantages are; no depth information, the need for access to both sides of the part, and the need for permanent location of equipment.

3.2 Ultrasonic Pulse Echo (PE)

In Pulse Echo mode a single transducer operates as both a transmitter and receiver. The ultrasonic transducer sends a pulse into the part. The pulse reflects from the back surface of the part. The receiver detects the reflected pulse. The time delay between pulse transmission and reception is a measure of the part thickness. If a flaw is present the pulse reflection from the flaw return sooner than that from the normal back surface of the part. The main advantages to this method are; depth measurements, the equipment is portable, and inspection is possible from one side of the part. The disadvantages are; the inspection is very time consuming, and there is no permanent record of the inspection.

3.3 Acoustic Emission (AE)

AE describes the elastic stress wave produced as a result of the application of stress. AE detects stress waves using sensitive piezo-electric transducers. The patterns of the stress waves give information on defect type and location. The main advantage is the detection of defect growth throughout the part while loading. The disadvantage is no defect size or depth information.

4.0 NDT EQUIPMENT DESCRIPTION

4.1 Ultrasonic (Pulse Echo)

The ultrasonic inspection system used was a Krautkramer Branson model USD-1. The transducer was a Zero Interface Probe (ZIP), which is a 0.5 mhz, 1.0 inch diameter, with a 0.600 inch delay line. The USD-1 is capable of digitalizing and storing waveforms from the CRT display onto removable bubble memory modules. This unique feature allows comparison of waveforms after each critical test phase. A Hewlett-Packard model 7550A plotter was used for plotting digitized waveforms.

4.2 Acoustic Emission

Development of the Acoustic Emission system was by Physical Acoustics Corporation for Morton Thiokol Inc. Figure 1 shows the components of the system. A brief description of the components is as follows:

[6] Physical Acoustics 3000/3004 Acoustic Emission analyzers. The 3000/3004 Acoustic Emission analyzer has four AE channel input with up to 4 load inputs. The digitized AE signal data from each transducer displays in real time on the computer CRT.

[6] HD-10 Winchester hard disk drives for data storage.

[6] Servogor 460 strip chart recorder. The strip chart recorder monitor AE events versus time and load.

[4] Physical Acoustics Model FRP-1. The FRP-1 records AE signal information from sixteen transducers. It prints a hard copy of AE sensor activity and amplitude at selected test points during the test.

[88] Physical Acoustics R15I transducers. The R15I is a piezoelectric transducer with an integral 40 db amplifier. The peak resonance is 150 khz. The R15I transducers are coupled to the FWC with hot melt glue. The transducer locations are shown in Figure 2.

Morton Thiokol Acoustic Emission personnel have modified the above equipment to optimize its use in composite testing as follows:

The modification of the Physical Acoustics 3000/3004 allows high speed data output to strip chart recorders. The off-the-shelf model has an output of approximately 100 events per second per channel. The modified unit records 2500 events per second per channel. High speed data acquisition is important when testing the FWC.

The Physical Acoustics FRP-1 modification raised the event detection threshold to 0.1 volts. The off-the-shelf model has a threshold of 0.01 volt. The higher threshold is necessary to prevent saturation of the FRP-1 during high event rates.

Special software for Morton Thiokol developed by Physical Acoustics Corporation allows for data filtering and replay on the IBM-PC. This enhances the data interpretation over the conventional 3000 computer.

The Morton Thiokol developed SIMUL-START unit starts or stops data acquisition of all test units simultaneously. It also inserts a time cursor into the data of each recording device.

5.0 PRETEST EVALUATION OF THE TEST ARTICLES

The NDT of STA-2A breaks into two groups:

(1) Pretest evaluation of the test articles,

(2) NDT inspections before, during, and after test loadings at MSFC.

The pretest evaluation consists of inspection by SUTRA before hydrotest, Acoustic Emission during hydrotest, and Pulse Echo after SUTRA and hydrotest. No inspection found any significant defects.

The NDT inspections that occurred at MSFC are the primary subject of this report. Pulse Echo inspections were performed per document STW7-3236, after assembly into test stand, after completion of test phases 5, 7, 8, and 9, on impact areas and any time Acoustic Emission data indicated defect growth. Acoustic Emission monitored all tests.

5.1 Pretest Evaluation of STA-2A Aft Segment (DA-005)

5.1.1 SUTRA

The SUTRA inspection of the Aft Segment found no reportable defects. The SUTRA map is shown in Figure 3.

5.1.2 Acoustic Emission

The Acoustic Emission data during hydrotest displays 3 areas of AE activity:

[1] from 0 to 58 inches aft of the Forward Joint at 250 degrees,

[2] from 0 to 36 inches aft of the Forward Joint from 240 to 340 degrees, and

[3] from 0 to 36 inches forward of the Aft Joint at 40 to 140 degrees.

The data gave no indication of the onset of failure.

5.1.3 Pulse Echo

Hercules personnel accomplished the Pulse Echo inspections after SUTRA and hydrotest, no reportable defects were found.

5.2 Pretest Evaluation of STA-2A Forward Segment (DF-004)

5.2.1 SUTRA

Hercules personnel accomplished two SUTRA inspections before hydrotest. The inspections found no reportable defects. The SUTRA map is shown in Figure 4.

5.2.2 Acoustic Emission

AE had two areas of activity:

[1] From 0 to 36 inches aft of the Forward Joint from 160 to 360 degrees.

[2] 220 inches aft of the Forward Joint at 120 degrees.

The data gave no indication of the onset of failure.

5.2.3 Pulse Echo

The inspections found no reportable defects.

5.3 Pretest Inspections at MSFC

Before test loading at MSFC a point scan inspection was performed as outlined in STW7-3236. The screen display for each point was stored on bubble memory. These recordings became the base line for all future inspections. The waveforms of the current inspection were superimposed on the CRT screen over the baseline points, any changes were then noted.

A Pulse Echo inspection was performed on the areas listed in DR #4421 and DR #4473. These areas were hit or scuffed during shipping, installation, or instrumentation of the segments. Figures 5-8 show the results of the inspection. Items 3, 4 and 5 had no indications of subsurface damage. Bob Anderson of Hercules reviewed the recorded scans; Item 1 was not a delamination and was present on the sutra map. Interpretation of the recorded scans suggest Item 2 to be a delamination . This area was inspected after each high pressure load. No growth was seen during any inspections.

6.0 ACOUSTIC EMISSION MONITORING OF STA-2A DURING TESTING

6.1 Phase 1B, Acoustic Emission Cycle

This test was performed on 30 January, 1985 per "Test and Checkout Procedure FWC-SS-TCP-001" to determine the AE characteristics of the FWC. Pressure loads were applied as shown in Figure 9.

The data signifies the STA-2A segments had no defect growth during this loading. Figure 10 shows the number of total events recorded at each sensor location. The number of total events is fewer than that of the previous AE test due to the initial matrix damage having occurred on the former test. Sensor locations 56, 79, 85, and 88 had slightly higher than average AE activity. All sensor locations had similar total events during the load hold, with good event roll-off during the hold. The pressure relief valve system masked any possible AE activity during download of pressure.

6.2 Phase 2, Aft ET Attach Point Influence

This test was performed in five load conditions from 4 March, 1985 through 6 March, 1985 per "Test and Checkout Procedure FWC-SS-TCP-008". Test loads are shown in Figure 11.

The AE data observed during Test Phase 2 shows the segments had no defect growth. The total number of AE events was very low compared with the previous hydrotest. Figure 12 shows the total event range recorded at each sensor location. All sensor locations had fewer than 10 events recorded during the load hold. No emissions occurred during the download of pressure.

6.3 Phase 3, Aft Et Attach Point, Influence Test With Internal Pressure

This test was performed on 12 March, 1985 per "Test and Checkout Procedure FWC-SS-TCP-010". Test loads are shown in Figure 13.

The AE data signifies defect growth during Test Phase 3 near sensor locations 55, 56, 57, 60, 65, and 71. The total event range activity of each sensor location is shown in Figure 14. The sensor regions listed above were the only sensors to exceed 3000 events. Figure 14 shows many sensors exceeded 1000 events. All sensors had good event roll-off during load hold. Sensor locations 4 and 80 detected minor activity during the download of pressure. Sensor locations 57 and 60 were the only sensors to have long duration events.

The results of the post test visual inspection are as follows:

SENSOR LOCATION	REASON FOR EMISSIONS
4	SENSOR UNBONDING FROM CASE
55,56,57,65	SEPARATION OF MACHINED OFF STIFFENER RIB
60	BLISTER ON MACHINED OFF RIB
71	SEPARATION OF THE FORWARD STIFFENER RIB
80	NO DEFECTS FOUND

6.4 Phase 4, Aft ET Attach Point, High Q Boost

This test was performed on 12 March, 1985 per "Test and Checkout Procedure FWC-SS-TCP-010". Test loads are shown in Figure 15.

The AE data shows that activity occurred at sensor locations 10, 33, 45, 48, 54, 55, 57, 60, 77, and 85. Figure 16 shows the total event range of each sensor location. This test phase has significantly more total events recorded than prior tests. The Aft Segment had more active regions than the Forward Segment. The load hold data differs from previous tests. This is due to continued AE activity past one minute into the hold by sensor locations 77 and 85. The data shows a rapid increase in rate at 712 psi. This gives a felicity ratio of 0.97, which signifies that there is no significant damage occurring until exceeding 712 psi. The relief valve noise masked emissions during download.

The results of the post test visual inspection are as follows:

SENSOR LOCATION	REASON FOR EMISSIONS
10	NOTHING FOUND
33	GIRTH GAGE SEPARATED FROM CASE
45	CABLE BUNDLE RIPPED TAPE FROM CASE
48	GLUE ON SENSOR SEPARATED FROM CASE
54,55,57,60,61	MACHINED OFF STIFFENER RING SEPARATED FROM CASE
77	BUILD UP OF FORWARD RING UNBONDING FROM CASE
85	NOTHING FOUND

6.5 Phase 5, Aft Et Attach Point, Lift Off

This test was performed on 14 March, 1985 per "Test and Checkout Procedure FWC-TCP-011". Test loads are shown in Figure 17.

The AE data shows continued damage growth to the machined off Stiffener Rib area and Forward Stiffener Rib. AE activity increased rapidly when the load exceeded 900 psi. This gives a felicity ratio of 0.96. The active areas are near sensor locations 54, 60, 61, 71, 74 and 77 (Figure 18). All areas had good event roll-off during load hold.

A post test Pulse Echo inspection was accomplished after Phase 5. The point scan recordings were the same as before test Phase 1. Correlation between the AE active areas, Pulse Echo and visual inspections are as follows:

SENSOR LOCATION	REASON FOR EMISSIONS
54, 60, 61	MACHINED OFF STIFFENER RIB UNBONDING (VISUAL)
71, 74, 77	FORWARD STIFFENER RIB UNBONDING (FIGURE 19)

6.6 Phase 6, Forward ET Attach Point, Influence

This test was performed on 3 April, 1985 per "Test and Checkout Procedure FWC-TCP-012". Test loads are shown in Figure 20.

The AE data shows no significant defect growth. The Aft Transition region had unusual emissions during the load hold. However, the low number of total events is not indicative of significant damage. Figure 21 shows the total event range of each sensor location. All sensor locations had good event roll off during load hold. Sensor locations 4 and 20 had events during download of pressure. A Pulse Echo inspection found no damage in this area. This small number of events could be noise from a load cell.

6.7 Phase 7, Forward ET Attach Point Lift-Off

This test was performed on 15 April, 1985 per "Test and Checkout Procedure FWC-TCP-013". Test loads are shown in Figure 22. This test was performed in two parts due to premature automated load system dumping. Acoustic Emission monitored both test loads. The AE data showed activity near sensor locations 27, 30, 54, 60 and 71. The event range activity of each sensor is shown in

Figures 23 and 24. The AE events versus load curve is shown in Figures 25 and 26. Figure 26 shows a non-linear increase in events after 100 percent load. The early event activity came from the previously mentioned sensor locations. This gave a felicity ratio of 0.91. This data indicates damage was near sensor locations 54, 60 and 71. The relief valve noise masked emissions during download of pressure.

A post test Pulse Echo inspection revealed the Stiffener Ribs unbonding. The Forward Rib was approximately 90% unbonded. The Aft Rib was 35% unbonded. The outer composite layer began separating from the layer below it, adjacent to the machined-off Stiffener Rib repaired region. Figures 27-31 show the inspection results in more detail.

The point scan inspection of the Transition regions occurred after phase 7. Noticeable changes occurred in the waveforms on the Forward Segment. The changes were a reduction in amplitude of some peaks and increased amplitude in others. These points are at 286-291 degrees on the Forward Transition region and 255-265 degrees on the Aft Transition regions. None of these waveforms represent a delamination. The new waveforms were recorded for future comparison.

6.8 Phase 8, Forward Et Attach Point, Maximum Axial Acceleration

This test was performed on 5 April, 1985 and 8 April, 1985 per "Test and Checkout Procedure FWC-TCP-015". Test loads are shown in Figure 32. Acoustic Emission monitored all tests.

The AE data shows no significant defect growth during this test phase. Figure 33 shows the total number of events recorded at each sensor location. AE activity was evenly distributed throughout the case. The AE activity increased when the load exceeded 750 psi. This gives a felicity ratio of 1.05. All sensors had good event roll-off during the load hold. No long duration events occurred. A post test Pulse Echo and visual inspection found no new damage.

6.9 Phase 9C, Prelaunch

Test phase 9C began 16 May, 1985 with completion on 24 July, 1985. Six test loads occurred up to and including test article failure. Table 1 shows and explains each test load. The applied loads are shown in Figures 34-39.

The first attempt to load the structure stopped at 60 percent limit load due to a malfunction of the instrumentation SIU.

The second loading of STA-2A occurred 17 May, 1985. The test was stopped due to high AE activity and unusual deflections in the case. The applied loads are shown in Figure 35. The real time AE data shows significant defect growth occurring in the Aft Segment, Aft Transition region near 160 degrees. Figure 40 shows the AE events versus load. A non-linear increase in AE events occurred when the load increased from 60 to 80 percent. During the 80 and 90 percent load hold the emissions continued to increase for the duration of the hold. During the reduction of load, friction type emissions occurred in the Aft Transition region. Figure 41 shows the total event range during load hold of each sensor location. Sensors 71, 84, and 85 were the predominant regions.

The AE data dictated the need for a follow up Pulse Echo inspection. The results of the inspection are shown in Figures 42 to 46. The Pulse Echo inspection was difficult due to the number of strain gages and wires attached to the case in this region. The Pulse Echo indications at less than .100 inches from the O.D. are due to a layer of Plastilock between ply layers fifteen and sixteen in the Transition region. NASA and MORTON THIOKOL stress analysis personnel determined this depth indication insignificant to structural integrity.

AE ACTIVE AREA	REASONS FOR EMISSIONS
71	DELAMINATION
84, 85	DELAMINATION

The forth loading occurred on 10 July, 1985. The applied load is shown in Figure 37. The test terminated due to the test loading system buckling during loading. The AE data shows no significant defect growth during this test. A Pulse Echo inspection found no defect growth.

The fifth load occurred 16 July, 1985. Figure 47, events vs. load, shows that significant defect growth occurred during this test phase. The known delamination area at 160 degrees on the Aft Transition region grew rapidly as the load exceeded 100 percent limit load. The data shows that the defect grew first in the circumferential direction, then in the forward direction, at higher load levels. The AE data indicated that Pulse Echo inspection was necessary. Results of the inspection are shown in Figure 48. Pulse Echo data confirms the AE data on growth direction and defect locations. The defect growth shown by Pulse Echo agrees closely with the predicated stress analysis model.

Completion of the third pre-launch ultimate stress test (sixth load) was on 24 July, 1985. AE sensor locations were changed to closely monitor the delamination growth. Figure 49 shows the new sensor locations. AE activity began to increase at the start of loading (Figure 50). From 0 to 100 percent limit load the AE data originated from the known delamination. As the load increased above 100 percent the AE activity shifted to the outside boundaries of the defect. During the loading above 115 percent limit load the AE data shows that the defect grew in the forward direction until failure. Figure 51 shows the total number of events recorded at each sensor location in the defect region. The most active areas were near sensor locations 76, 85, 86 and sensors 2, 3, and 6. Cumulative results of all Pulse Echo inspection of all AE active areas are shown in Figure 52. The Pulse Echo data confirms that delamination growth occured in the directions AE displayed in real time. Failure occurred in the location of unusually high AE activity noted during the first loading to 90 percent limit load. The AE data showing first hit and time of flight measurements recorded, indicate the failure occurred in the location shown in Figure 53. Figure 54 shows a topographical map of AE activity for the Aft Segment during failure load.

7.0 POST FAILURE INSPECTION OF SAMPLES

The samples cut from the STA-2A Aft Segment were representative of the different types of Acoustic Emission and Pulse Echo signals recorded during testing. Figure 55 shows the location from which the samples were cut. Only six post-failure samples were evaluated. The other samples were used by HERCULES and MORTON THIOKOL Composite Structures groups for further analysis. A discussion of each sample follows:

7.1 SAMPLE 9

The size and dimension of test sample #9 are shown in Figure 56. This sample was chosen because it is typical of the Pulse Echo signal seen in the Aft Segment Forward Transition regions. Area A had Pulse Echo indications at depths of 0.080 to 0.120 inches from the OD. This is typical of the plastilock unbonding or high porosity in the plastilock.

Figure 57 shows a side view of this area. The porosity is evident from 13.7 inches to 16.6 inches. A void exists in the composite from 14.7 to 16 inches. The plastilock porosity was measured with calipers to be 0.080 inches from the OD. The void was at a depth of 0.120 inches from the OD.

The Pulse Echo signal recorded at this location is shown in Figure 58. The waveform shows the near surface peaks to be predominate with peaks at the back wall depth being less than 10 percent of the screen height. Area B shows the same type Pulse Echo signal as found in A. This porosity is not as severe as area A. Both mechanical and Pulse Echo measurements shows depths of 0.080 inches.

7.2 SAMPLE 12

The location and dimensions of sample 12 are shown in Figure 59. This sample has two abnormal regions. Area A is plastilock with high porosity, area B is a delamination. Figure 60 shows the plastilock porosity at 28 inches to 30.5 inches with a mechanical measured depth of 0.080 inches. The delamination of area B had a mechanical measured depth of 0.230-0.245 inchs. The Pulse Echo depth was 0.260 inchs. The ultrasonic signal shown in Figure 61 displays that the near surface porosity blocks indications for backwall signals.

7.3 SAMPLE 17

Test sample 17 represents the forward edge boundary condition for the failure location. The forward boundary and depth information are critical for stress analysis and modeling. Figure 62 shows the sample dimensions and location of defects. Two defects are seen in this sample; Area A which is the forward boundary of the major delamination and area C which is an unbond of the Stiffener Ring build up region from the case. The Pulse Echo inspection at MSFC shows delamination growth of area A to be approximately 2 inches forward of the Stiffener Rib. Figure 63 shows a picture of this delamination. The Pulse Echo depth measurements of these flaws at MSFC gave an indication of 1.300 inches at point A and 0.530 to 0.547 inchs at point B from the OD. The measured mechanical depths from the OD are 1.480 inches for point A and 0.600 inch for point B. The full wave Pulse Echo signal for location A and B are shown in Figures 64-65.

Area C is representative of the build up area of the over wrap. The Pulse Echo indication displays a depth of 0.065 inch. Figure 66 shows the Pulse Echo signal from this region.

7.4 SAMPLE 18

Test sample 18 was chosen for the same reason as sample 17, it contains the forward edge boundary for the delamination growth. The inspection at MSFC indicated the delamination to extend approximately 2 inches beyond the Stiffener Ring at this location. A post test visual of this part shows the delamination terminated under the Stiffener Rib. This is shown in Figure 67. The inspection at MSFC indicated the depth to be 1.00-1.15 inches. The mechanical measured depth on the sample was 1.515 inches. There is a question of the origin of this particular sample since the post test ultrasonic results and visual examination conflict with the MSFC inspection of the forward growth boundary. Figure 68 shows the inspection results after the sample was cut out. This inspection shows no ultrasonic defect indication forward of the Aft Stiffener Rib. If the sample was taken from the area of 130 degrees instead of 140 degrees the post inspection results would confirm the inspection at MSFC. Figure 69 shows the waveform recorded from the sample at location B.

7.5 SAMPLE 19

Sample 19 was chosen because this was an AE active area generating friction type emissions. The Pulse Echo inspection at MSFC indicated this was a circumferential termination point of the major delamination. The origin and dimensions of the sample are shown in Figure 70. The reason for friction type AE are quite obvious from Figure 71. The interesting observation from this sample is that the Pulse Echo inspection from the OD showed areas A, B and C but did not show delamination F, G or H. The high porosity in the plastilock in this location blocked the detection of the delamination. Figures 72 and 73 show the waveforms recorded at the A and B locations.

7.6 SAMPLE 20

Figure 74 shows the origin and dimensions for sample 20. This sample was chosen because it was typical of the signals we thought represented areas of high porosity in the plastilock. Figure 75 shows the porosity in the plastilock, but it also shows delaminations below. The waveform from location A shows the peaks located at 0.470 inches from OD. A mechanical measurement shows the delamination to be located 0.415 inches. Figure 76 shows a good backwall signal from a good area of this sample beyond the layer of porosity.

8.0 SUMMARY OF NDT SAMPLES

The results from the post-test inspection of the samples shows the depth measurements taken at MSFC were accurate until exceeding .260 inches thickness. The data then shows that Pulse Echo measurements exceeded actual part thickness by 10 to 14 percent. The greater the thickness the more error. This error is due to the ultrasonic calibration block not being representative of the material measured. The step block used for calibration of the Pulse Echo equipment was made from joint material. The material measured was Transition and Membrane. Until the step block can be representative of the material to be measured, this type thickness error will continue to occur.

The mapping of forward boundaries of delaminations proved to be within the tolerance of the equipment. Using the ZIP probe, we expected the maximum difference between Pulse Echo boundary and visual boundary to be no greater than one half the diameter of the probe (i.e. one-half inch). In all cases except sample 18 this was found to be true.

The samples definitely show the short comings of the Pulse Echo inspection method used. The near-surface porosity blocked significant structural defects below. Once the insulator is installed, this blocks Pulse Echo inspection from the ID. STA-2A was, to a large extent, uninspectable, by the method used, in the Transition regions due to high porosity in the plastilock.

9.0 SUMMARY OF NDT RESULTS

The NDT performed on STA-2A shows how NDT can be used to assist Design Engineering in evaluating the structural integrity of composite test articles. During physical testing of a new composite part, defects and design deficiencies can lead to premature part failure. NDT must warn of these problems prior to part failure. Early warning provides designers the opportunity to check current stress modeling accuracy. Without NDT, design personnel must evaluate the pieces from the failure and theorize the failure. With the development of NDT, the failure can be monitored and models confirmed.

This is the first full scale SRM-FWC segment that utilized NDT to warn of impending failure. Acoustic Emission gave early warning of this failure. Pulse echo ultrasonic methods revealed size and depth of the defects. Although still a developing technology, AE proved it could give good correlation to physical damage occurring in the case during loading. AE's ability to monitor 100 percent of the composite in real time during test loading made it a critical tool for STA-2A testing.

The AE data from the first hydrotest indicated that the area of the eventual failure had a defect. However, the specific ultrasonic inspections were still developing and were unable to confirm this region at that time as an area of concern. Unfortunately, the more traditional ultrasonic methods carried more weight than the newer AE technologies in determining case reliability.

The following is a brief summary of the NDT events that occurred during each test phase.

Phase 1:
All channels show good roll-over during the load hold. Active sensors are 56, 79, 85, 88. Pulse Echo performed to establish the baseline for Pulse Echo points stored in bubble memory.

Phase 2:

No significant AE activity. Active sensor 16 showing 101-1,000 event range. No long duration events.

Phase 3:

AE activity indicates minor defect growth at sensors locations 55, 56, 56, 65, 71. Visually seen is a separation of the machined off Stiffener Ring of the Aft Segment, small separation on the build up region of the Forward Stiffener Ring. Sensor locations 60 and 61 show a blister on the machined off ring. Sensor location 80 shows no visible damage to account for increased AE activity. Sensors location 71 shows that the build up region of the Forward Ring separating from the case.

Phase 4:

AE activity continues during the load hold. Active sensors are 54, 55, 57, 60, 61 and 77. AE indicates new damage growth during loading from 712 psi and 930 psi. Visual examination shows the machined off Stiffener Ring separating from the case. Active sensor 77 shows the build up of the Forward Ring separating from the case.

Phase 5:

Active sensors 54, 60 and 61 visually shows new separation and new fiber breakage around the machined off Stiffener Ring. Active sensors 71, 74, and 77 shows visual separation of the build up region of the Forward Stiffener Ring increasing. Pulse Echo points taken after the phase shows no change in the waveforms.

Phase 6:

The area of the case near sensors 3 and 38 visually show no damage, although these sensors are active, their number of events is low. Active sensors 80, 81, 84, 85 and 88 were unusually active for the type of load applied.

Phase 7:

The total number of events are very low. Active sensors 3 and 38 shows no visual damage. Phase 7B shows non-linear growth increasing at 100% load. Active sensors 27 and 30 shows no damage to account for activity. Active sensors 54 and 60 visually shows the machined off Stiffener Ring debonding from the case. The first helical layer is debonding from the case. Activity from sensors 71 and 74 is from the debonding of the Stiffener Rings from the case. The felicity ratio of 0.91

indicates damage. Pulse Echo points scanned after the test phase shows a general change in waveforms. There is a major delamination of the Forward Stiffener Ring to case.

Phase 8:

AE data shows no major defect growth. AE shows a good felicity ratio. The Aft Segment shows a high number of events for the type of load, although all events are still within normal range. Pulse Echo and visual shows no new damage.

Phase 9:

The AE data indicated defect growth occurring in the Aft Segment, Aft Transition region at 160 degrees. The AE began increasing sharply as the load increased above 60 percent. AE activity continued during the 80 percent load hold. The test was stopped at 107%. A Pulse Echo inspection revealed a delamination occurred from 155 degrees to 175 degrees in the Aft Segment, Aft Transition from 8 to 30 inches forward of the Aft Composite edge. The Aft Segment failed in the location previously mentioned at 129 percent limit applied load.

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FIGURE 1. AE TEST SYSTEM LAYOUT

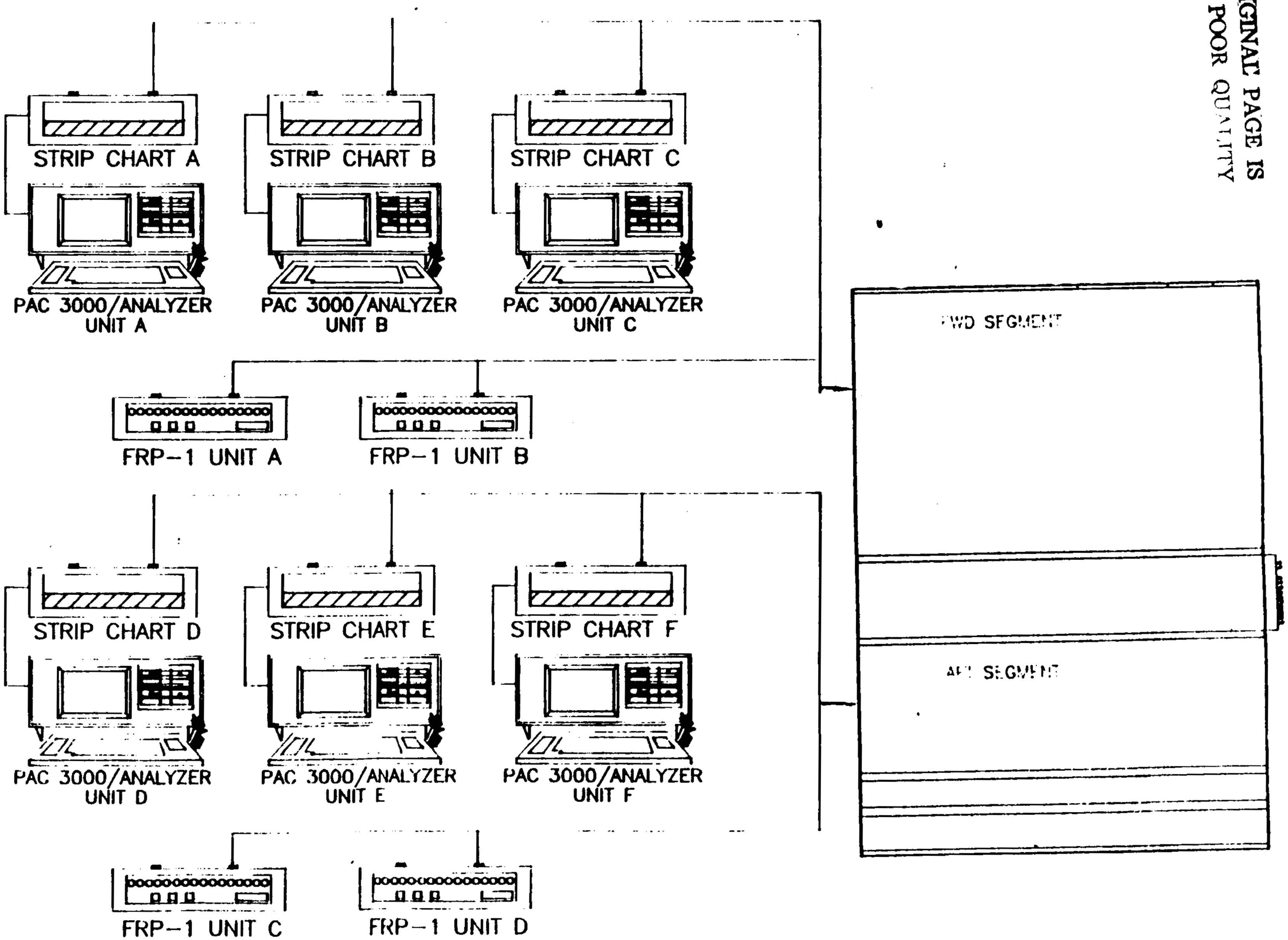

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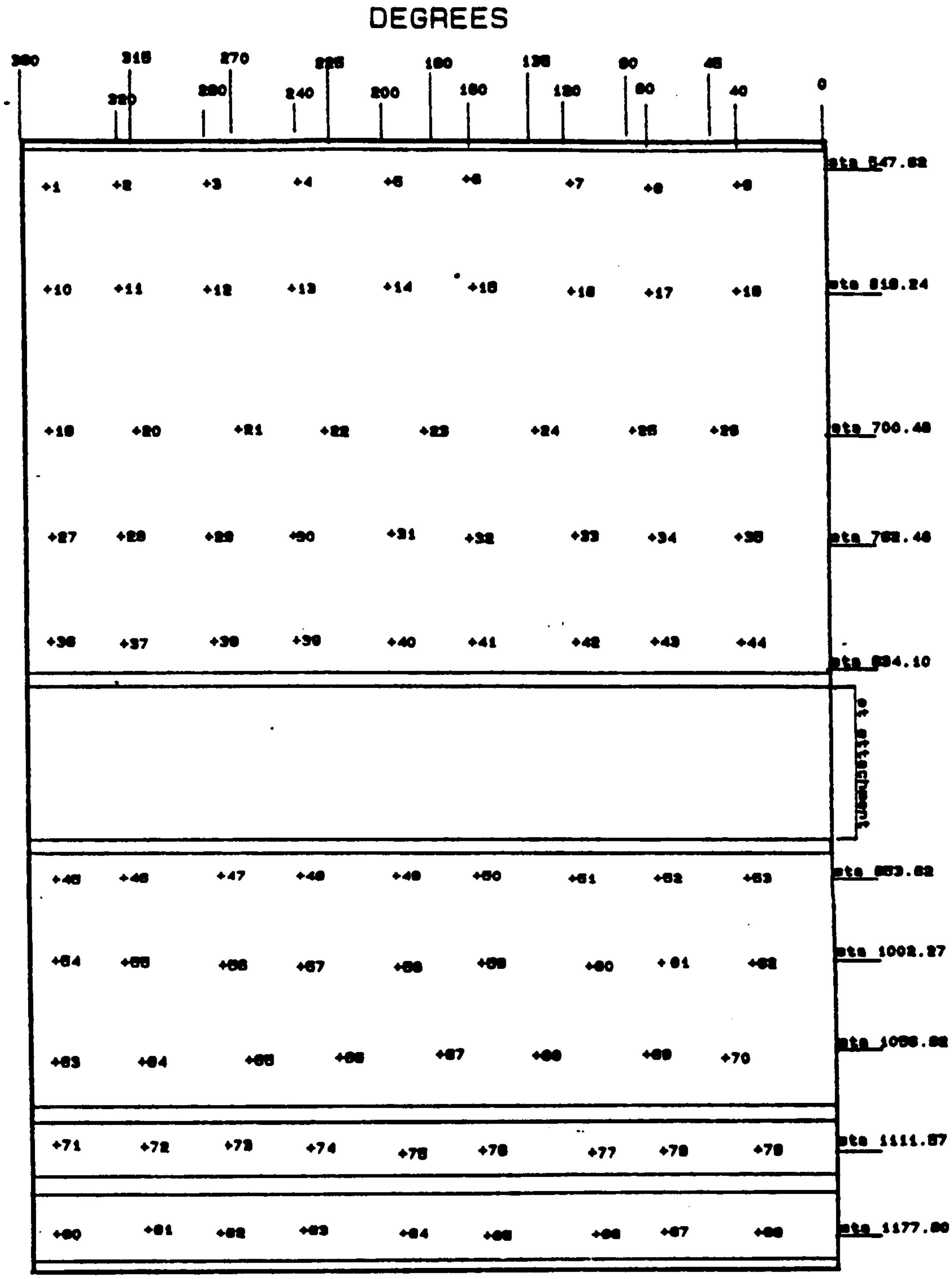
FIGURE 2. STA-2A SENSOR LOCATIONS



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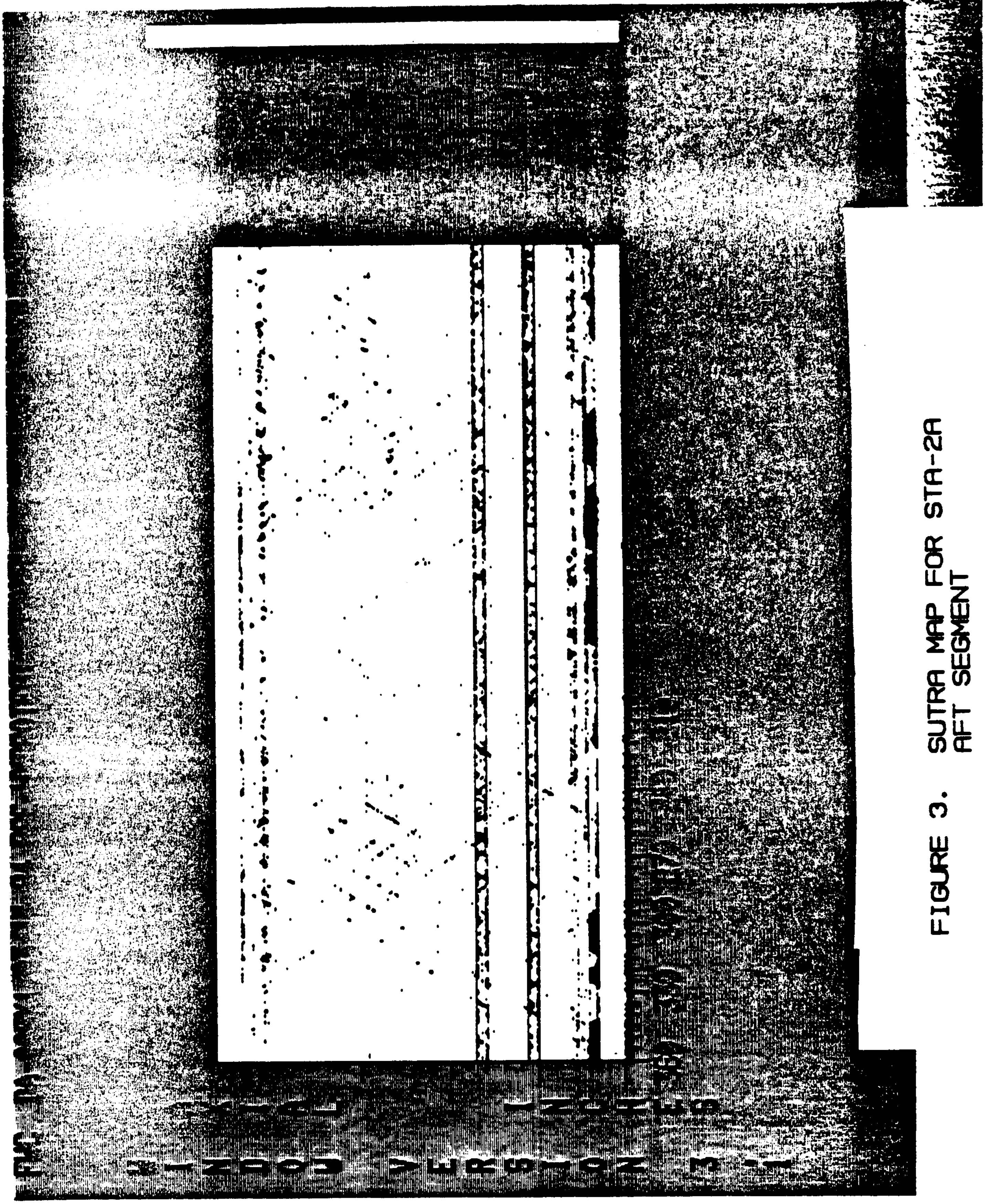


FIGURE 3. SUTRA MAP FOR STA-2A
AFT SEGMENT

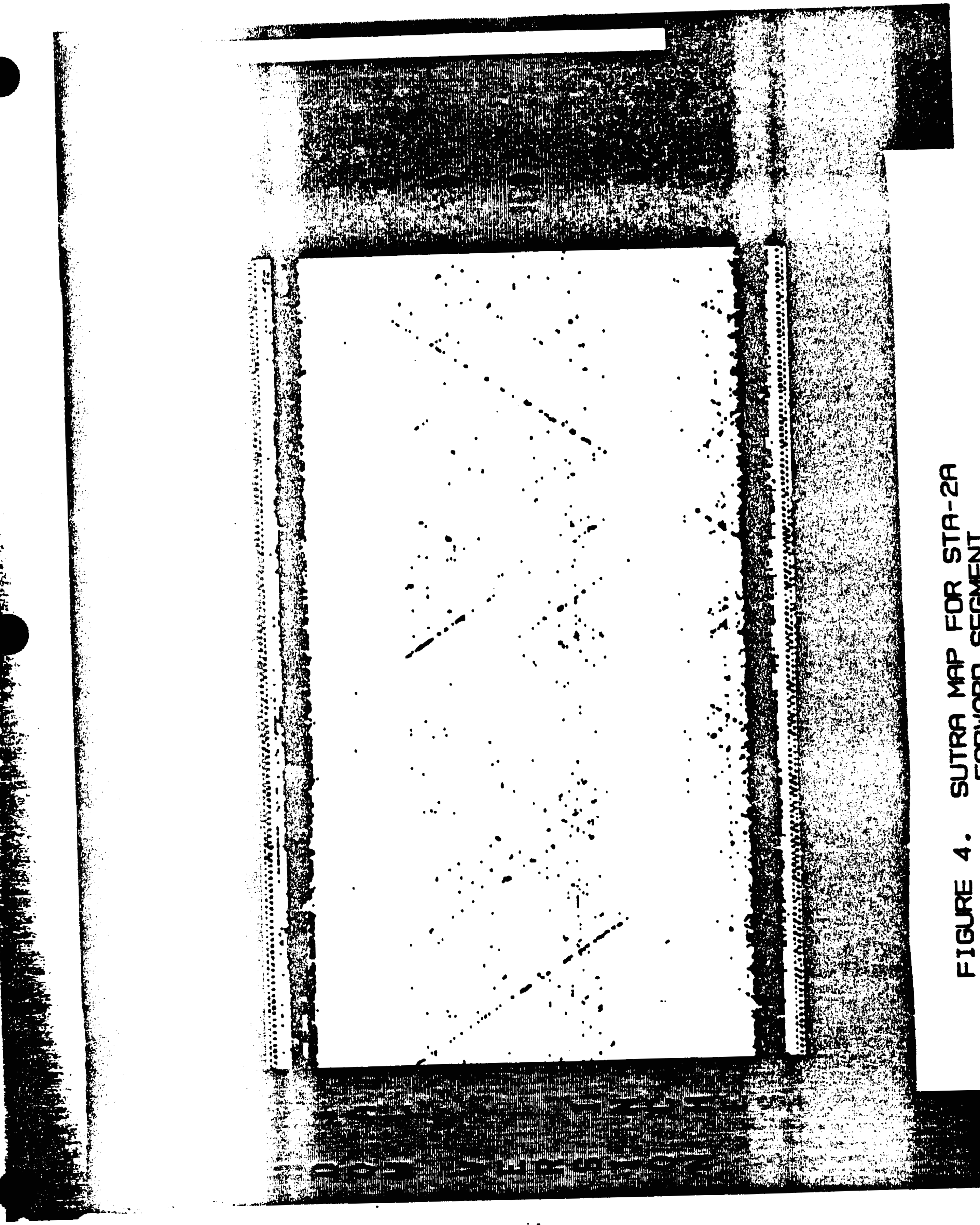


FIGURE 4. SUTRA MAP FOR STA-2A
FORWARD SEGMENT

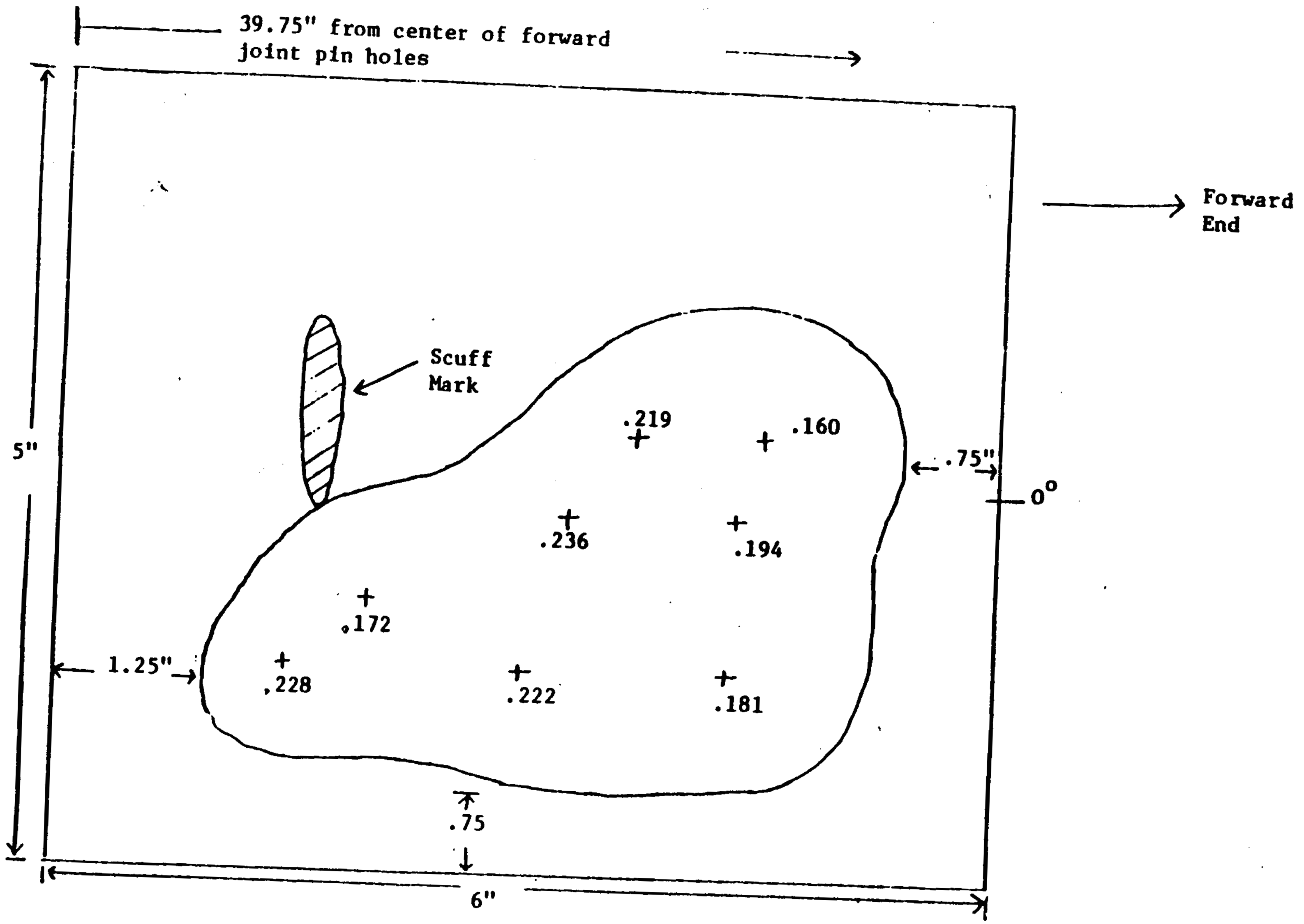
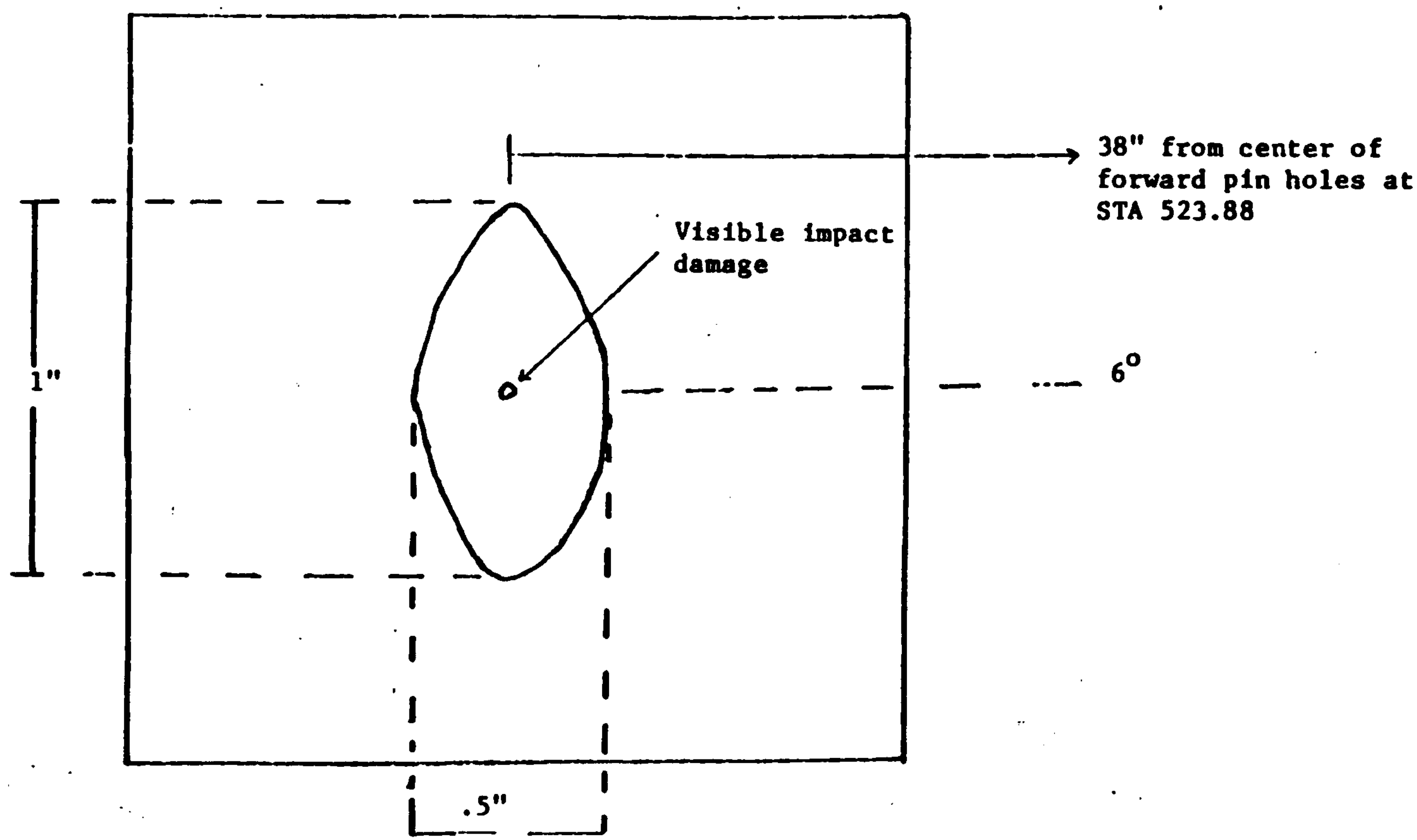


FIGURE 5. DR #4421. ITEM 1

FIGURE 6. DR #4421. ITEM 2



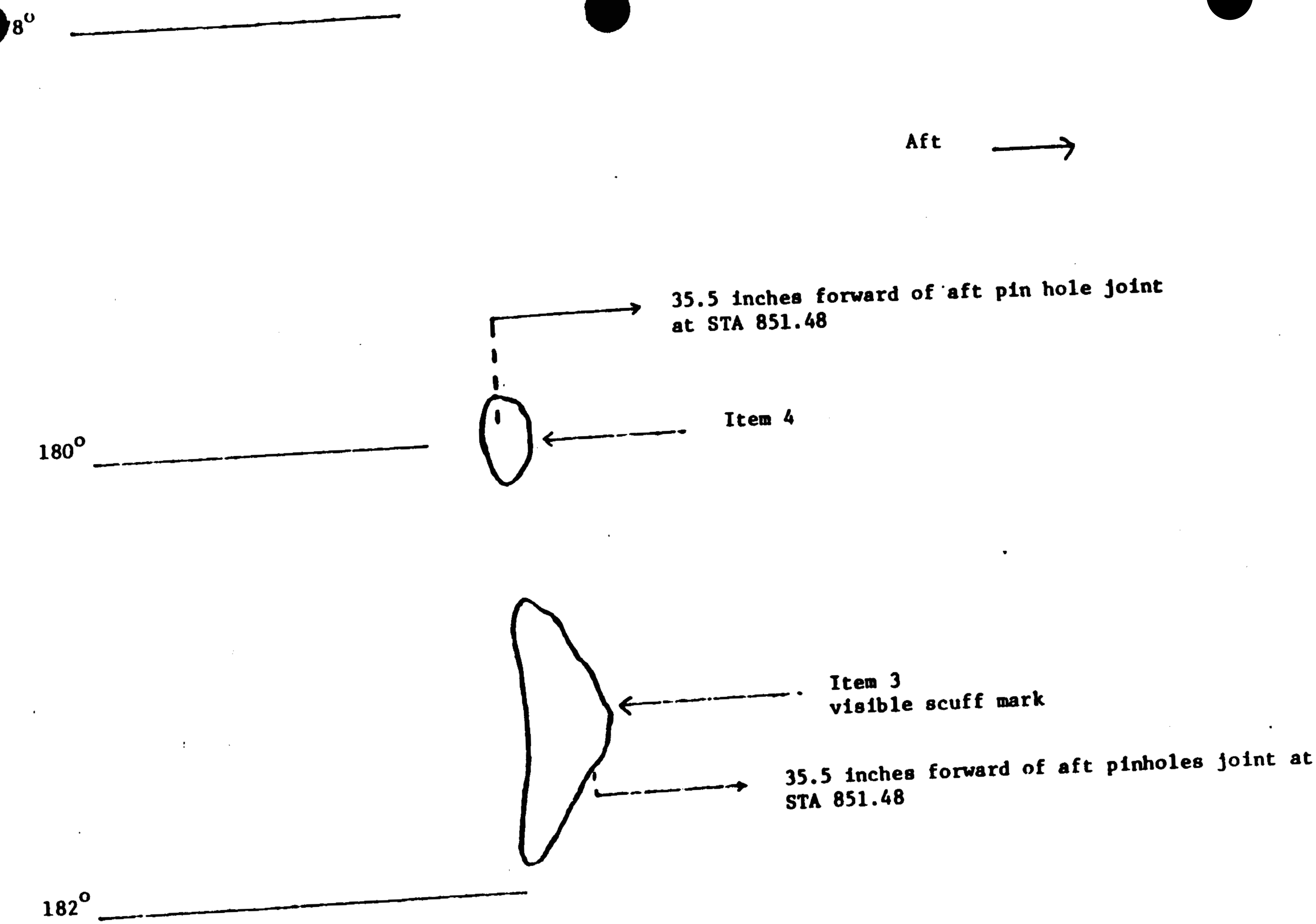
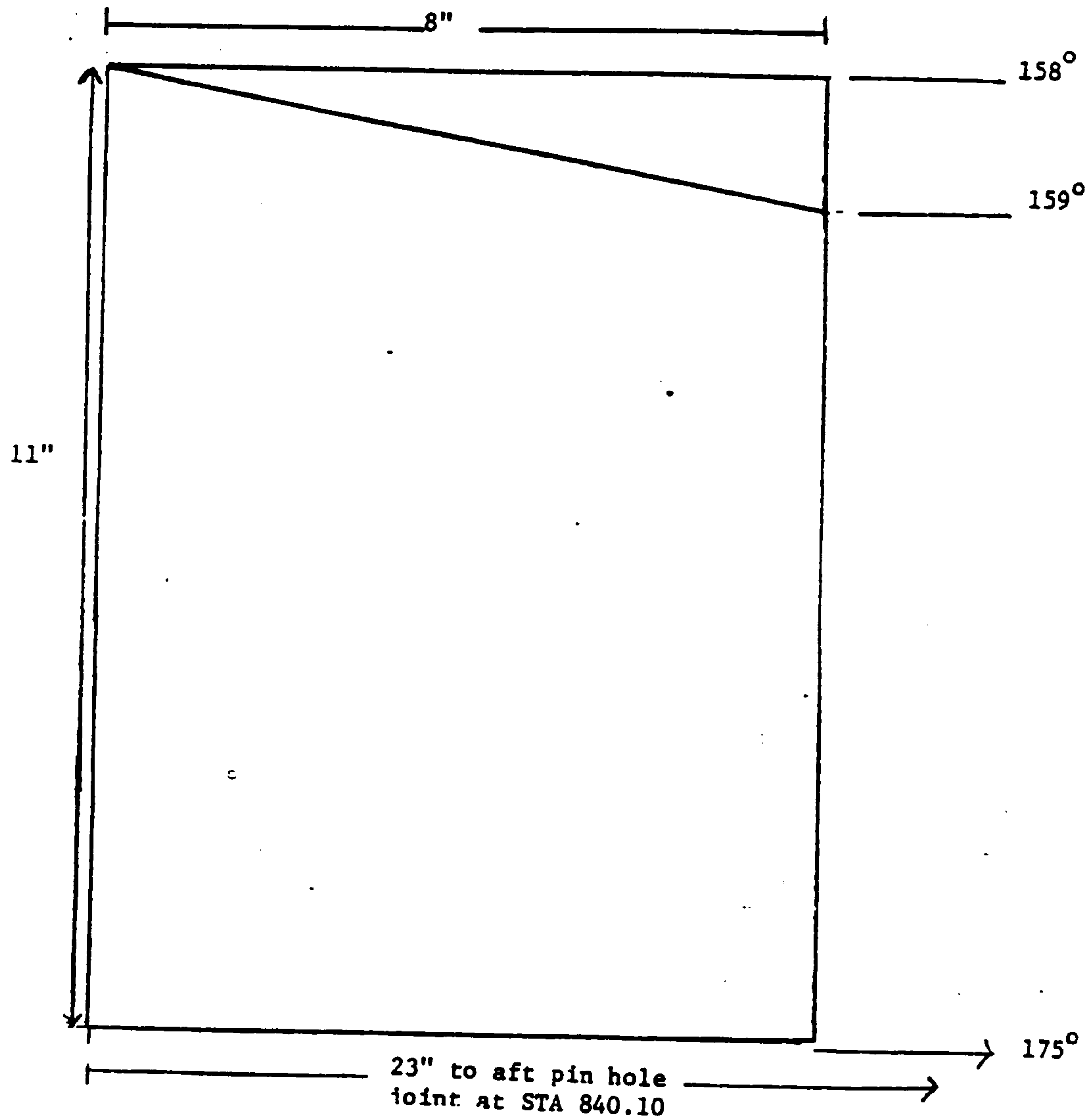


FIGURE 7. DR #4421. ITEMS 3 84

FIGURE 8. DR #4473, ITEM 1



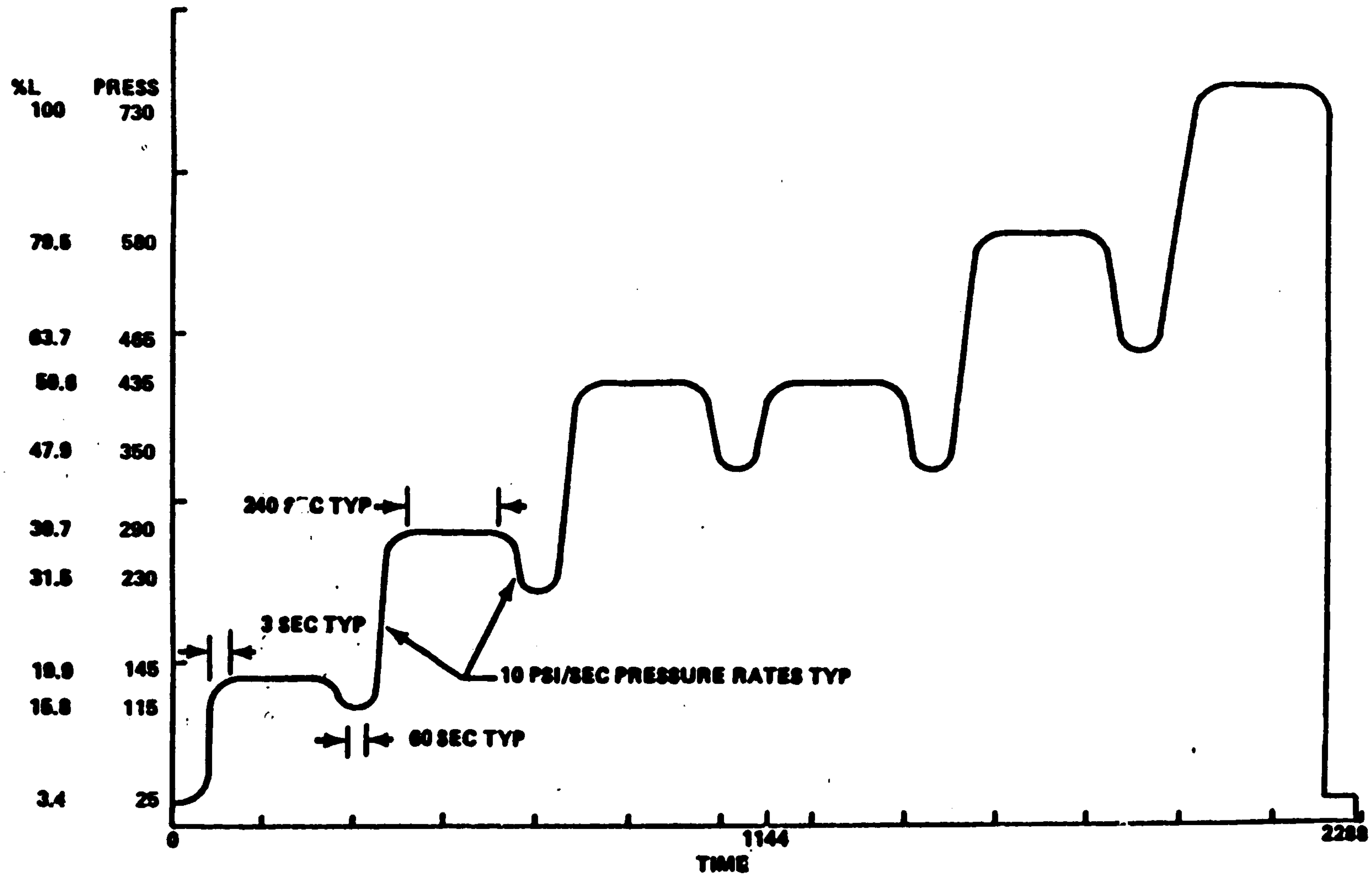
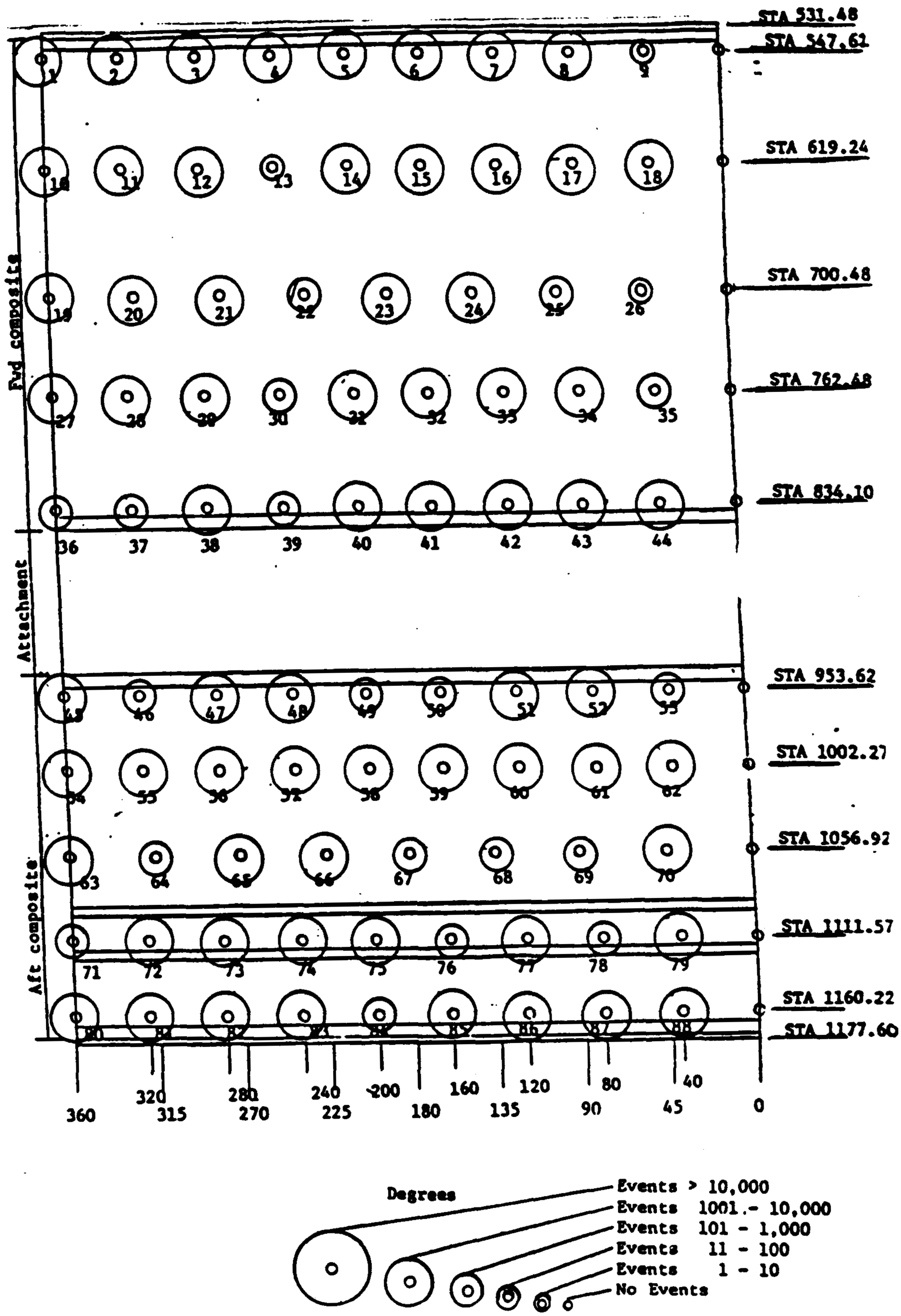
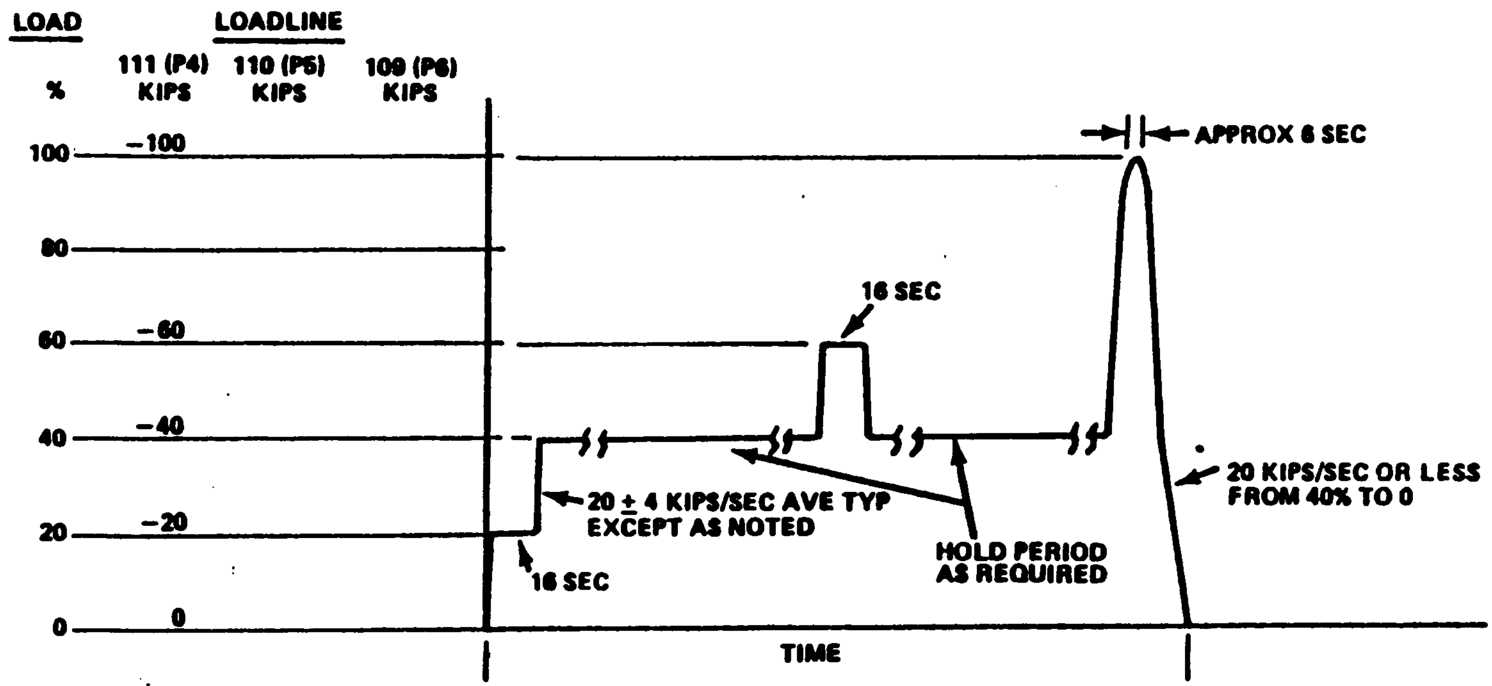


FIGURE 9. CHECKOUT TEST 1 PROFILE. PHASE 1B

FIGURE 10. TOTAL AE EVENTS PER SENSOR
TEST PHASE 1B

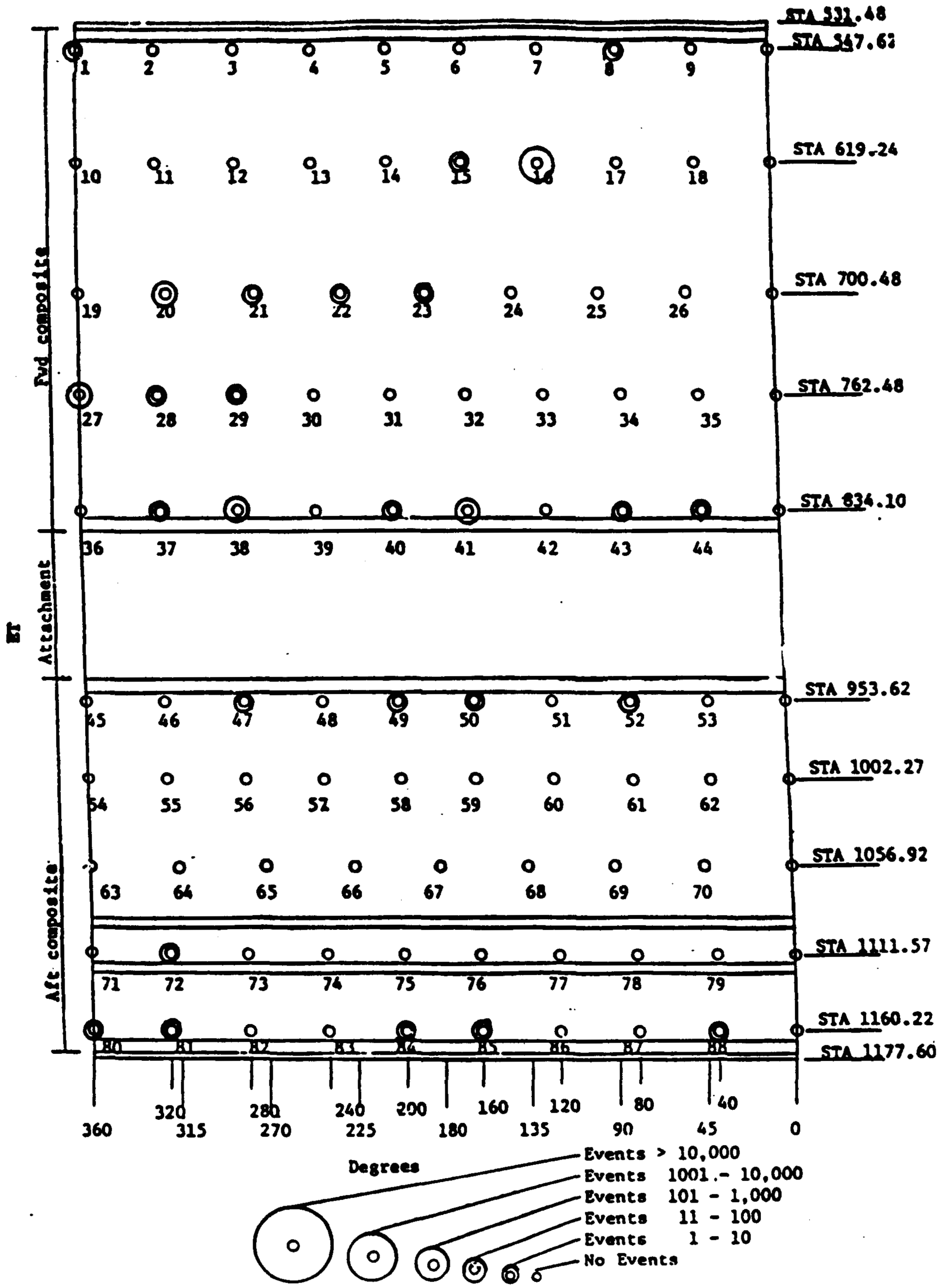


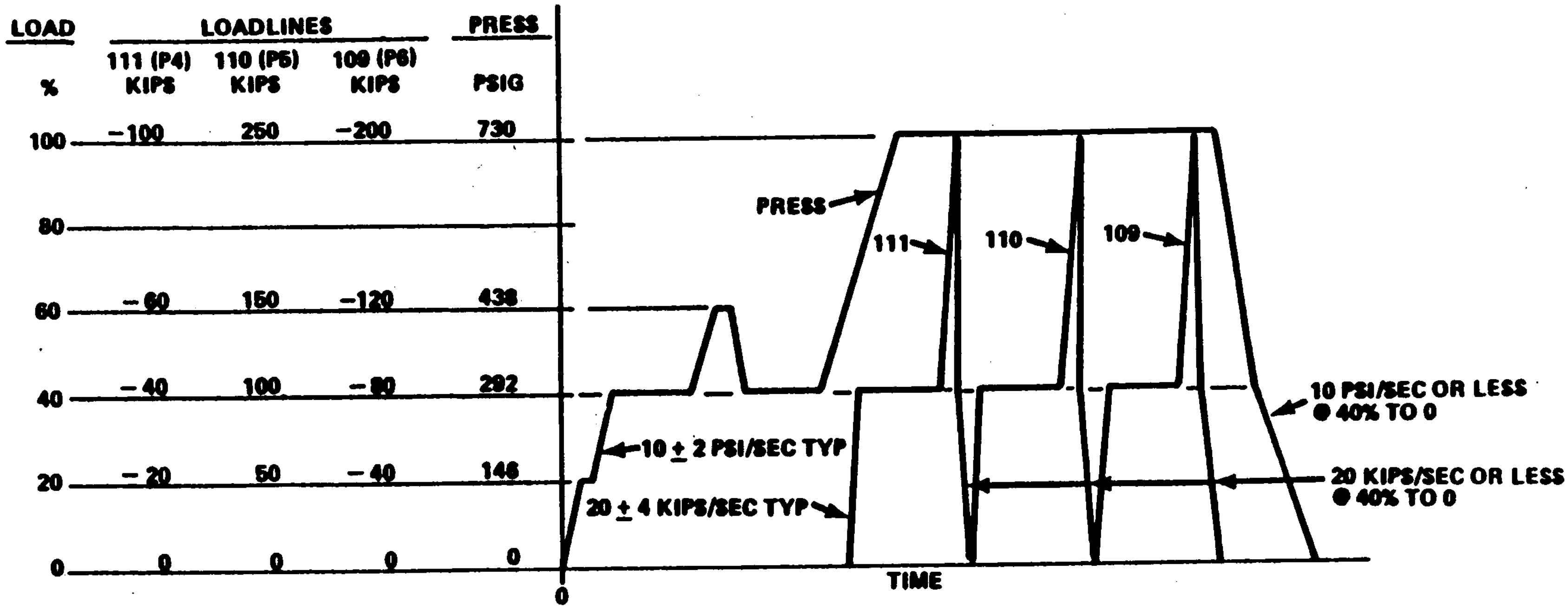


NOTES:
1. + DESIGNATES TENSION ON LOAD CELLS
2. − DESIGNATES COMPRESSION ON LOAD CELLS
3. TRANSIENTS ARE APPLIED AS A HAVERSINE (1 − COSINE)

FIGURE 11. PROFILE 1 TEST SETUP 1. PHASE 2 (CONDITION 1)

FIGURE 12. TOTAL AE EVENTS PER SENSOR
TEST PHASE 2

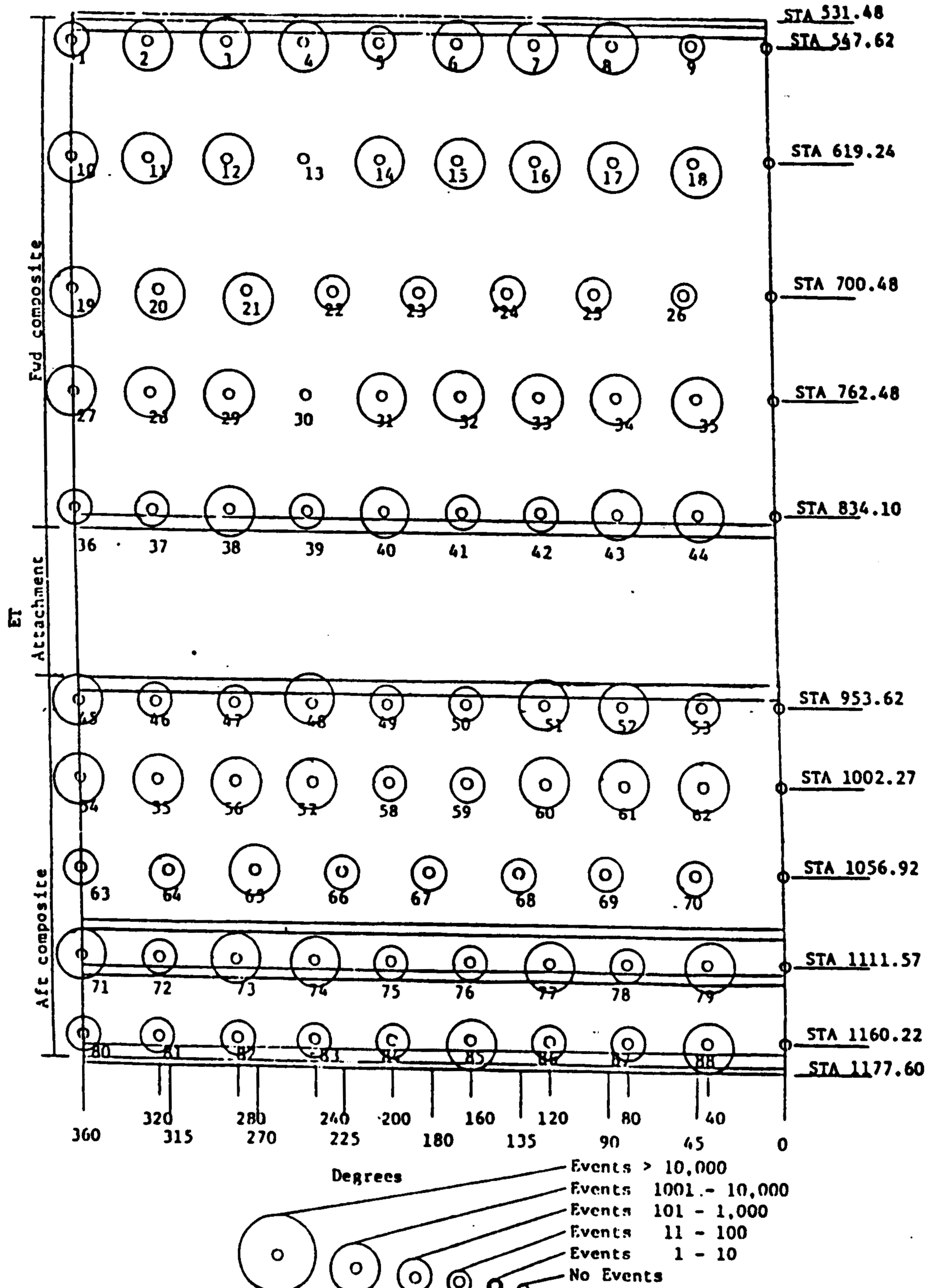




NOTES:
1. + DESIGNATES TENSION ON LOAD CELLS
2. − DESIGNATES COMPRESSION ON LOAD CELLS
3. TRANSIENTS ARE APPLIED AS A HAVERSINE $\frac{(1 - \text{COSINE})}{2}$

FIGURE 13. PROFILE I TEST SETUP 1, PHASE 3

FIGURE 14. TOTAL AE EVENTS PER SENSOR
TEST PHASE 3



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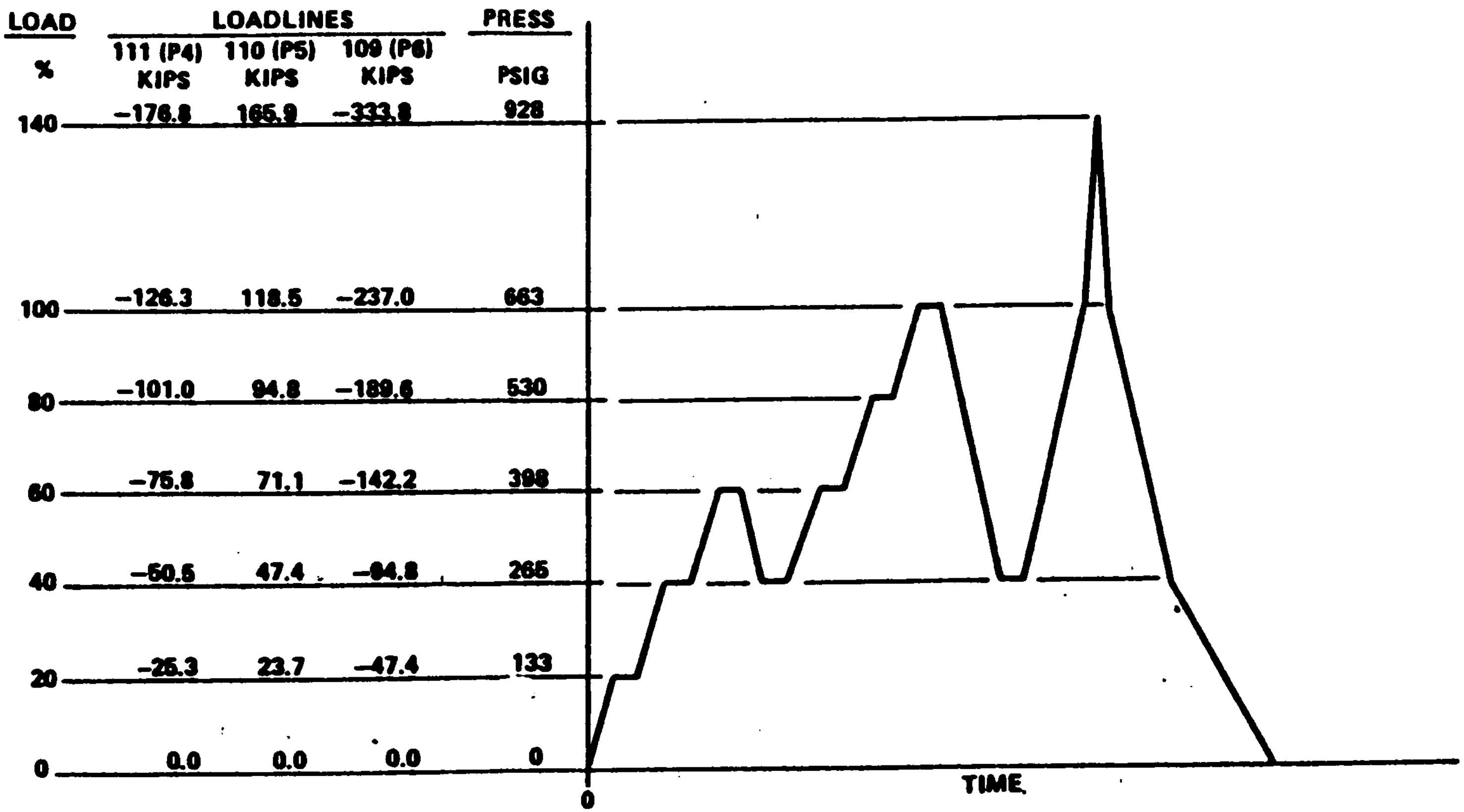
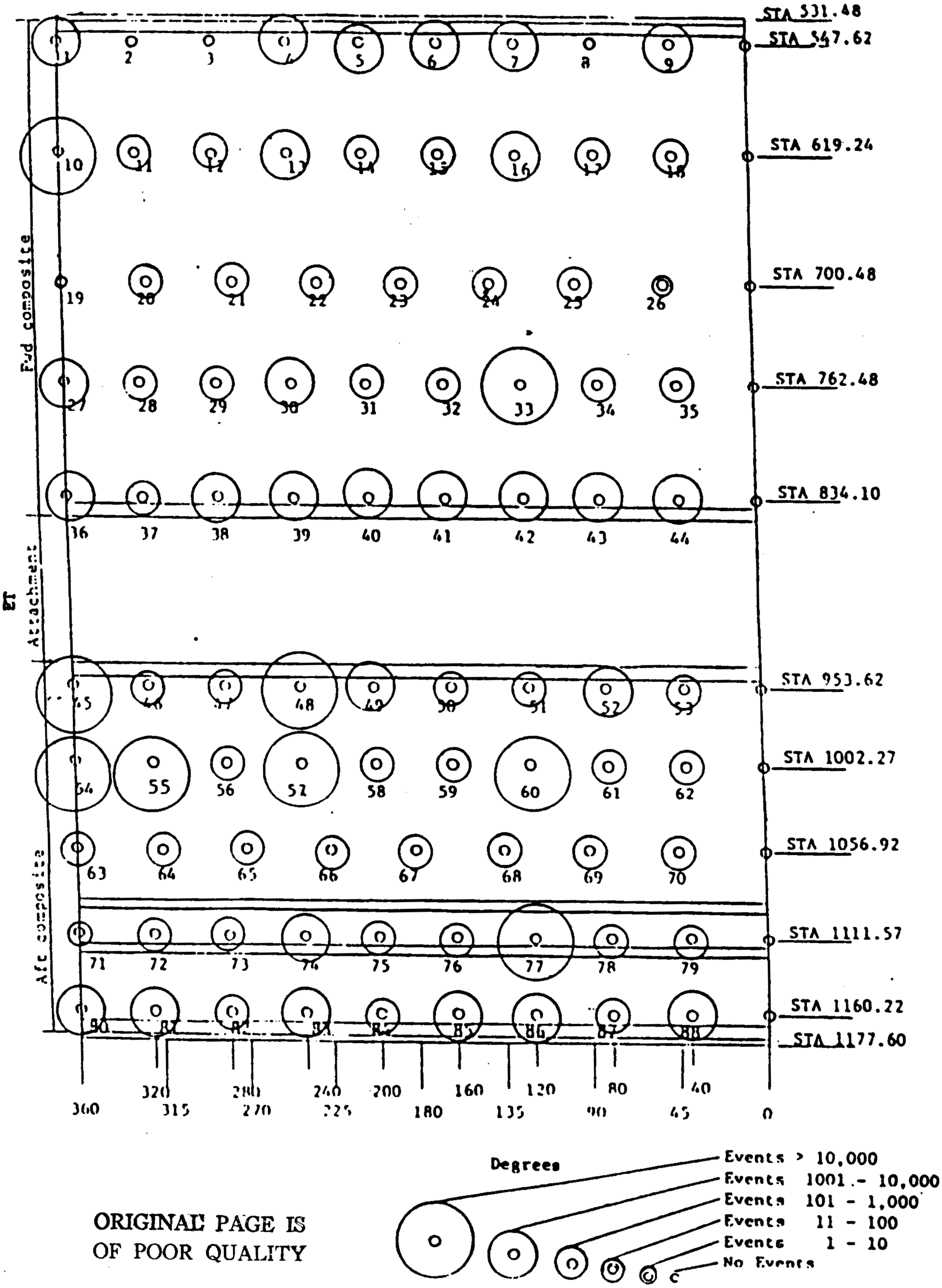


NOTES:

1. + DESIGNATES TENSION ON LOAD CELLS
2. — DESIGNATES COMPRESSION ON LOAD CELLS
3. TRANSIENTS ARE APPLIED AS A HAVERSINE $\frac{(1 - \text{COSINE})}{2}$

FIGURE 15. PROFILE 1 TEST SETUP 1. PHASE 4

FIGURE 16. TOTAL AE EVENTS PER SENSOR TEST PHASE 4



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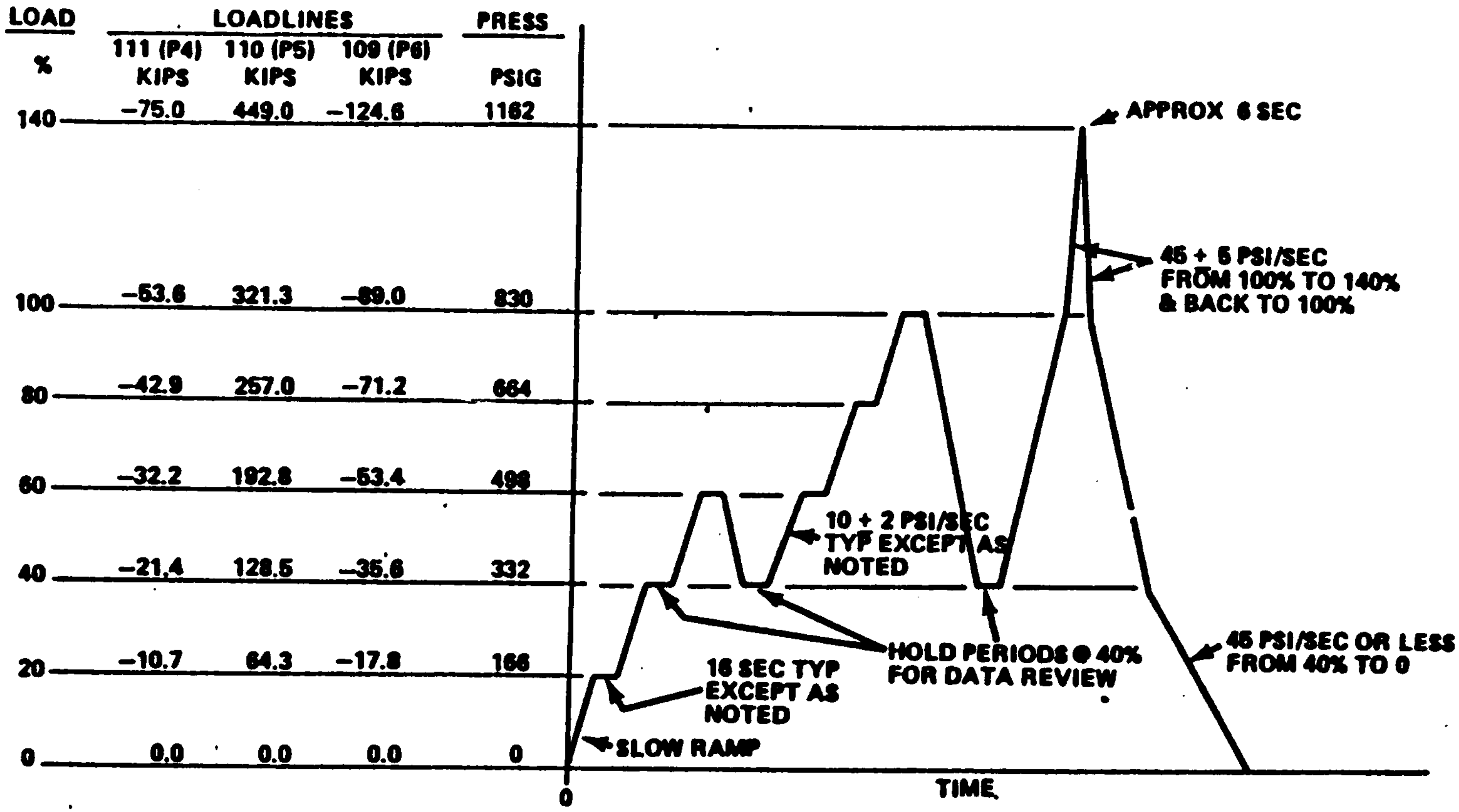

NOTES:

1. + DESIGNATES TENSION ON LOAD CELLS
2. — DESIGNATES COMPRESSION ON LOAD CELLS
3. TRANSIENTS ARE APPLIED AS A HAVERSINE $\frac{(1 - \text{COSINE})}{2}$
4. DESCRETE SCANS WILL BE MADE AT 0, 20, 40, 60, 40, 60, 80, 100, 40 PERCENTS

FIGURE 17. PROFILE 1, TEST SETUP 1, PHASE 5

FIGURE 18. TOTAL AE EVENTS PER SENSOR
TEST PHASE 5

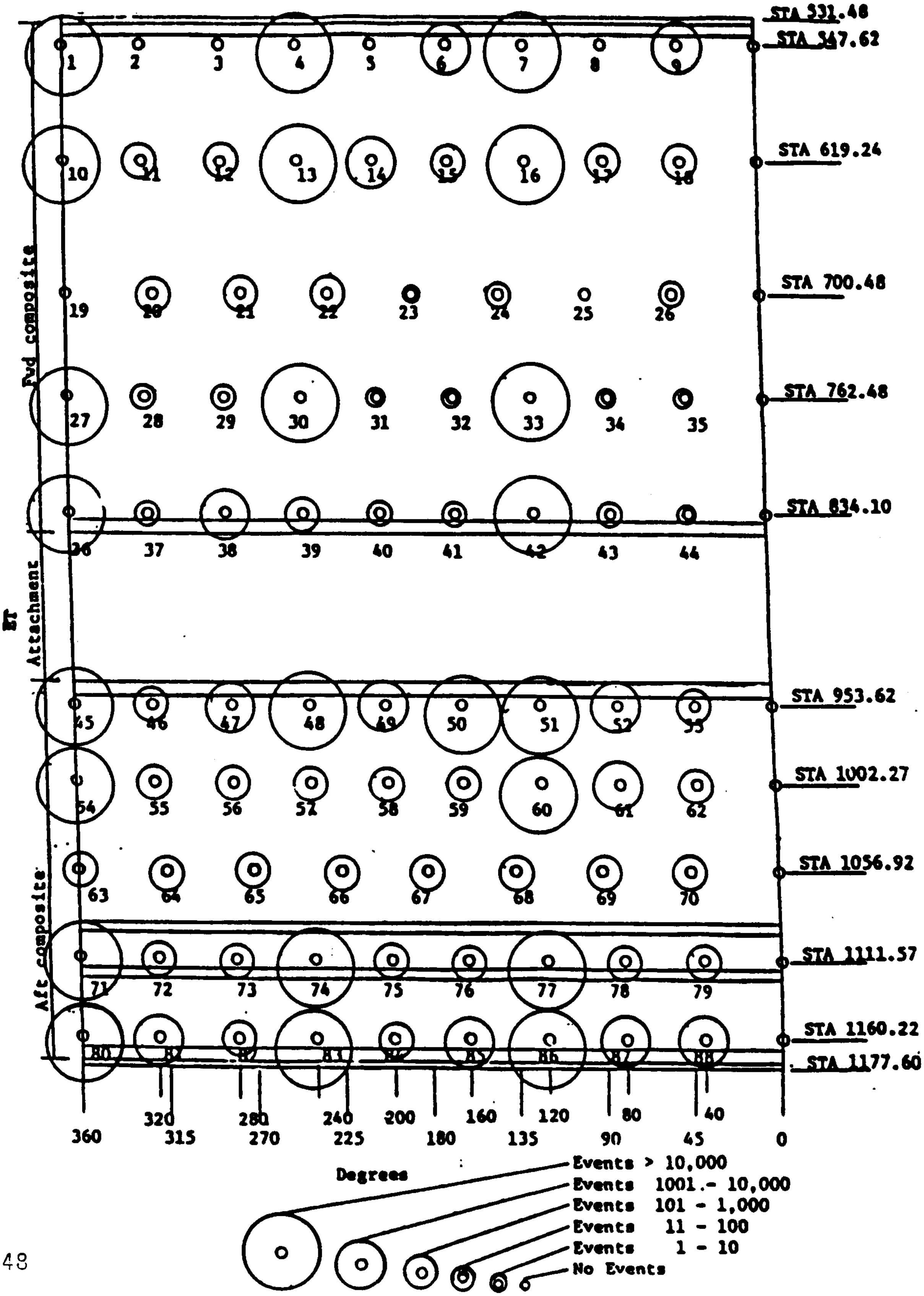

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FIGURE 19. STIFFNER RING INSPECTION AFT SEGMENT FWD RING

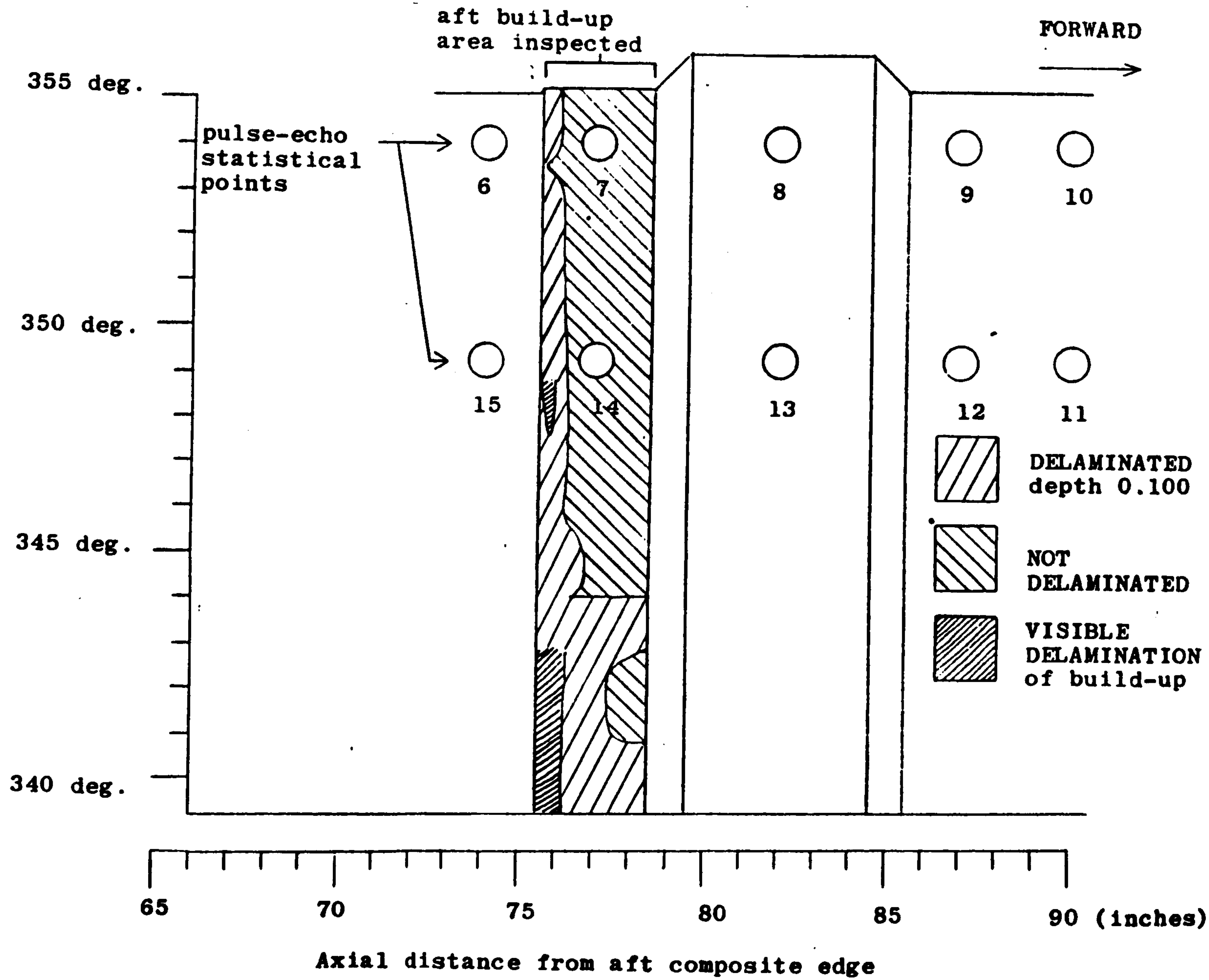

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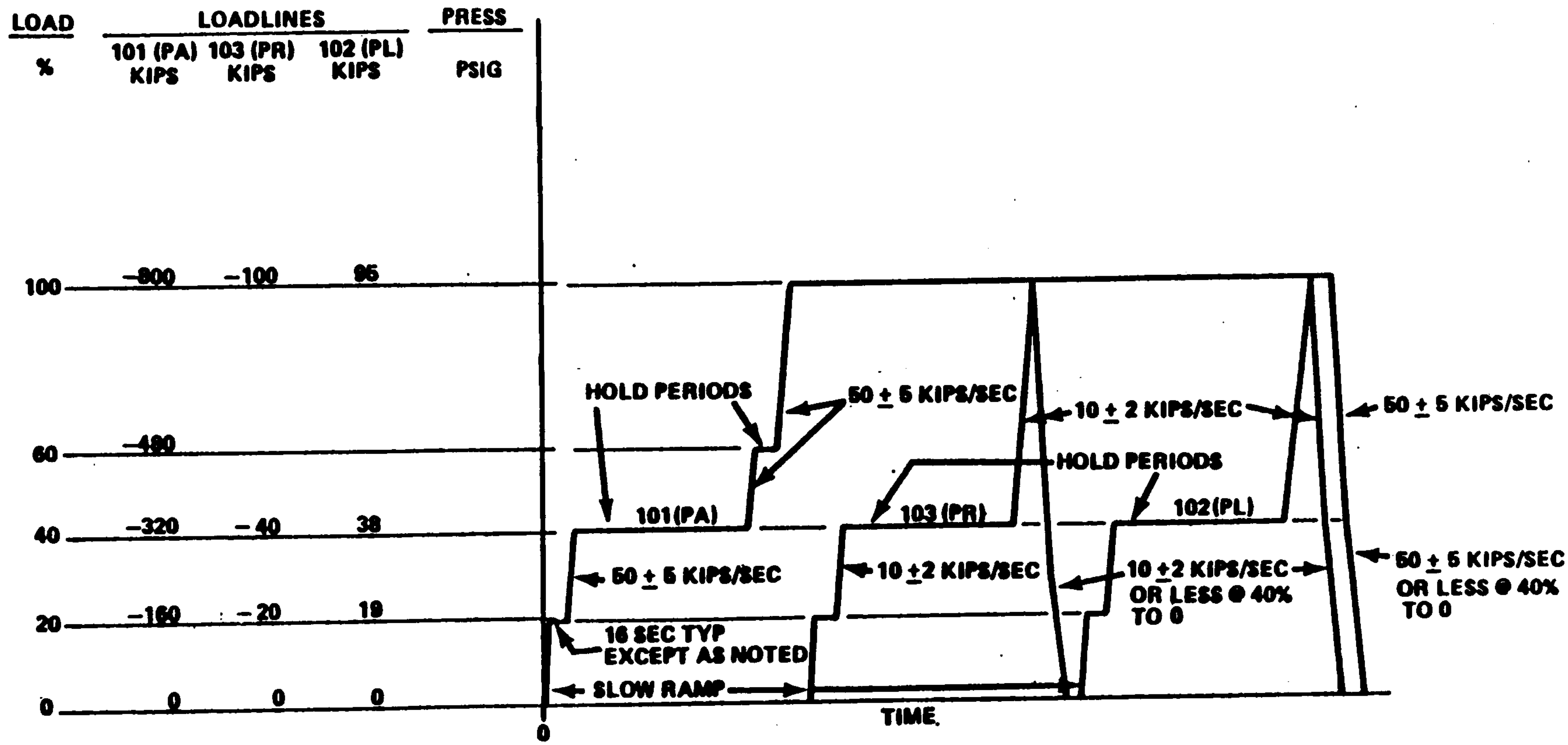
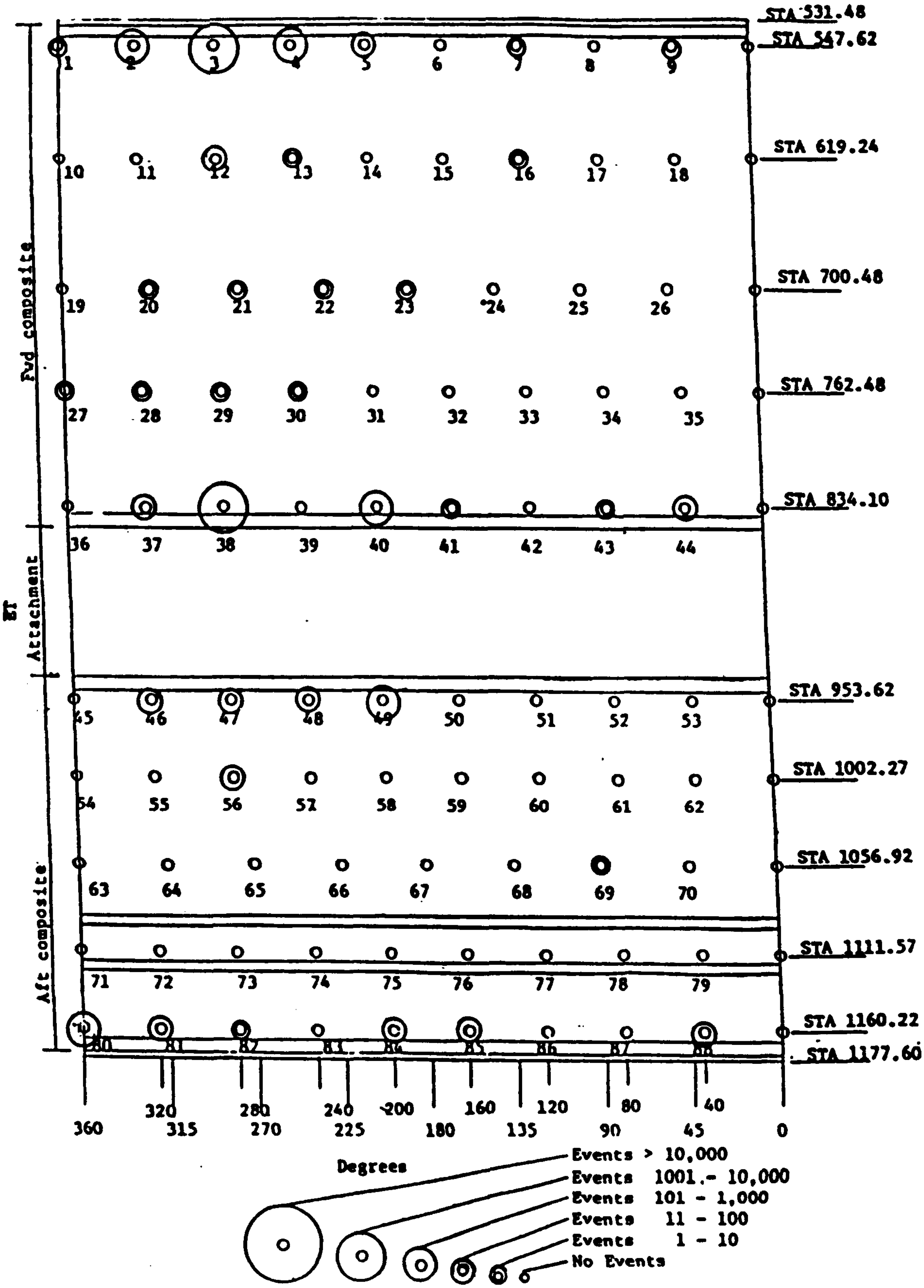
FIGURE 20. PROFILE 1 TEST SETUP 1. PHASE 6

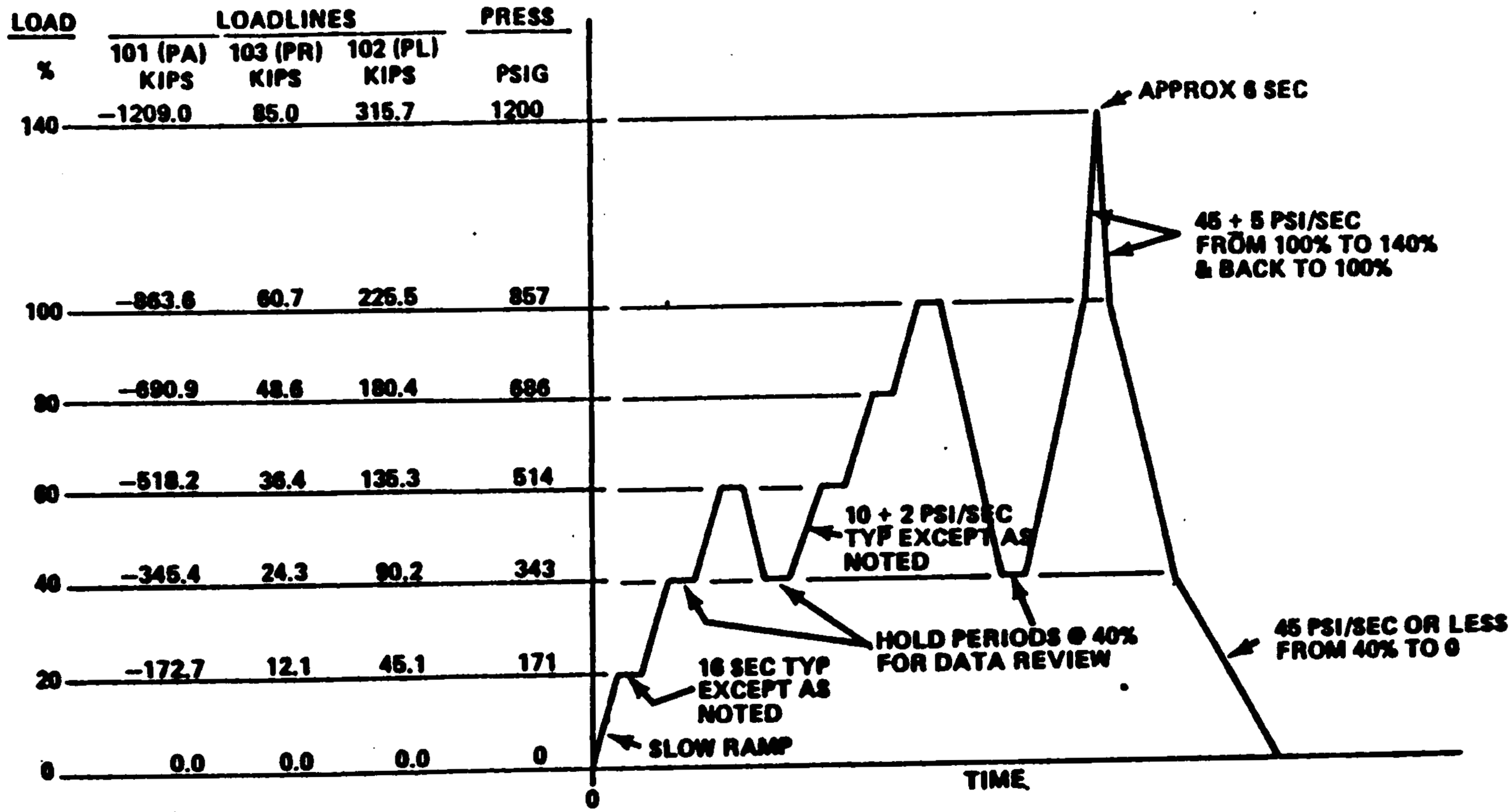


NOTES:

1. + DESIGNATES TENSION ON LOAD CELLS
2. − DESIGNATES COMPRESSION ON LOAD CELLS
3. TRANSIENTS ARE APPLIED AS A HAVERSINE $\frac{(1 - \text{COSINE})}{2}$
4. DESCRETE SCANS WILL BE MADE AT 0, 20, 40, 60 PERCENTS FOR PA & 0, 20, 40 PERCENTS FOR PR & PL
5. HOLD PERIODS AT 40 & 60 PERCENTS ARE FOR DATA REVIEW

FIGURE 21. TOTAL AE EVENTS PER SENSOR TEST PHASE 6





NOTES:

1. + DESIGNATES TENSION ON LOAD CELLS
2. – DESIGNATES COMPRESSION ON LOAD CELLS
3. TRANSIENTS ARE APPLIED AS A HAVERSINE (1 – COS) / 2
4. DESCRETE SCANS WIL 0, 20, 40, 60, 40, 60, 80,
5. APPLICATION & RELE. PA, PR, PL WILL BE IN TO PRESSURE

FIGURE 22. PROFILE 1, TEST SETUP 1, PHASE 7

FIGURE 23. TOTAL EVENTS PER SENSOR LOCATION TEST PHASE 7A

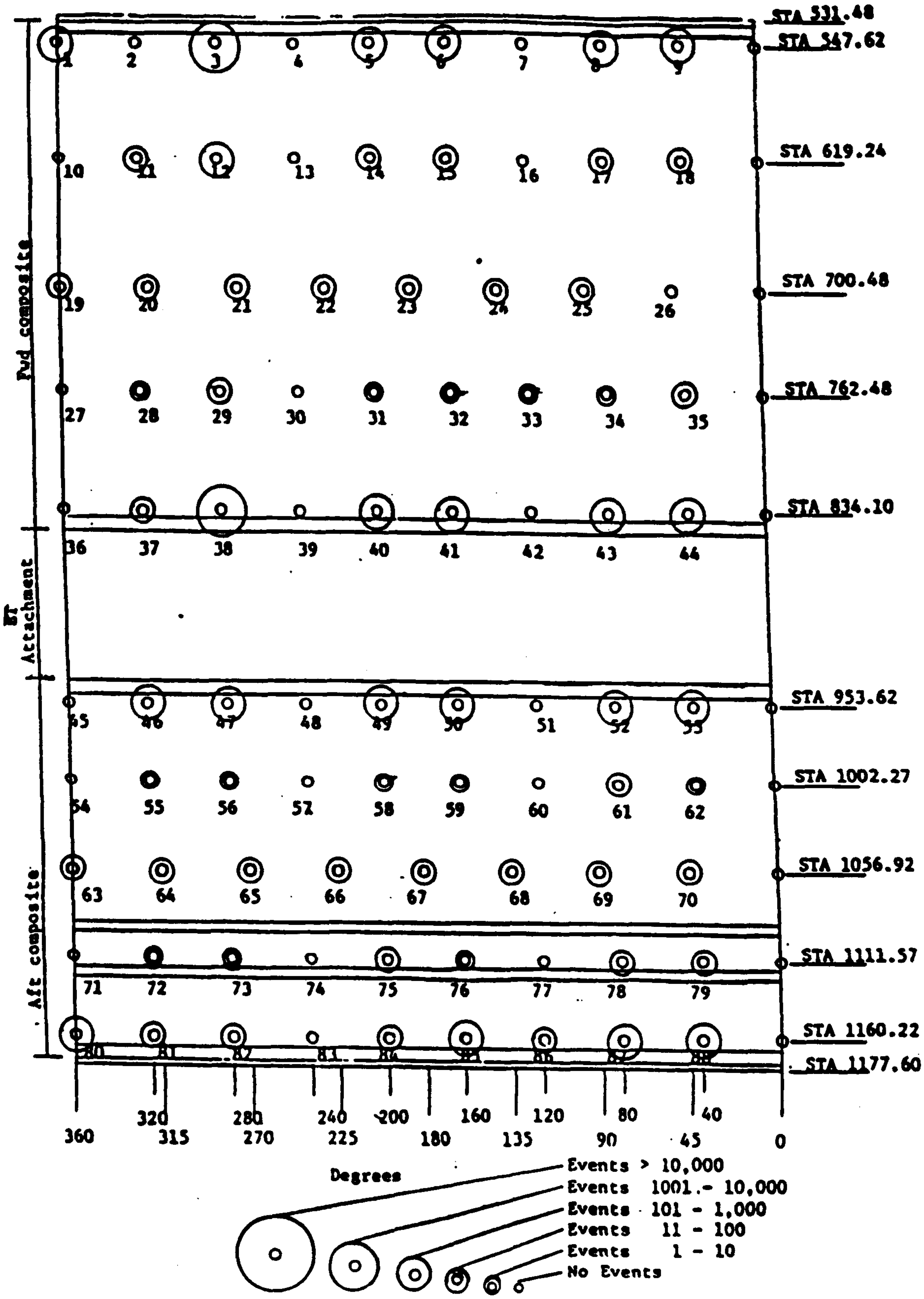


FIGURE 24. TOTAL EVENTS PER SENSOR LOCATION
TEST PHASE 7B

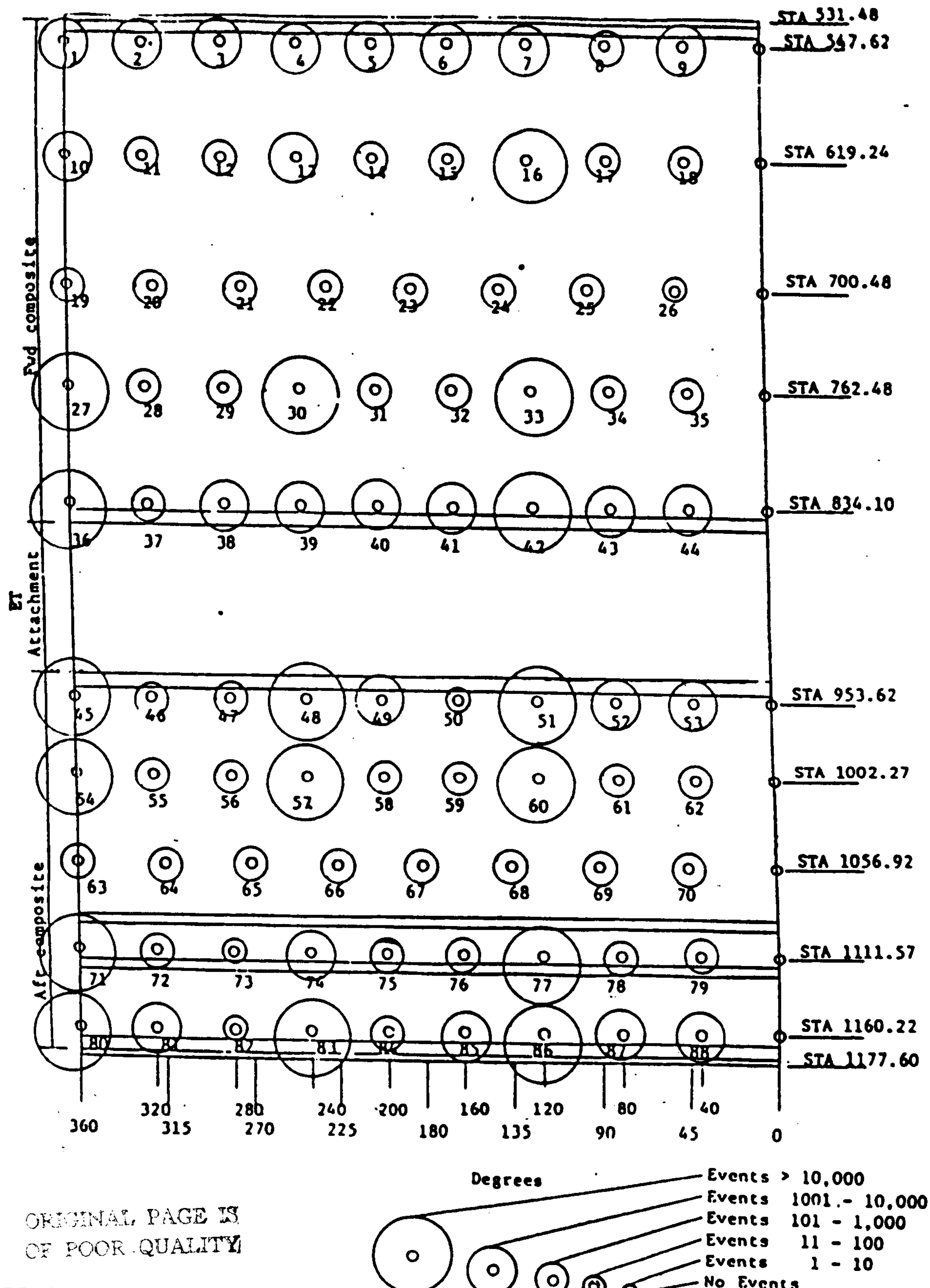


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FIGURE 26. STA-2 PHASE 7B
CUMULATIVE EVENTS VS. LOAD CYCLE

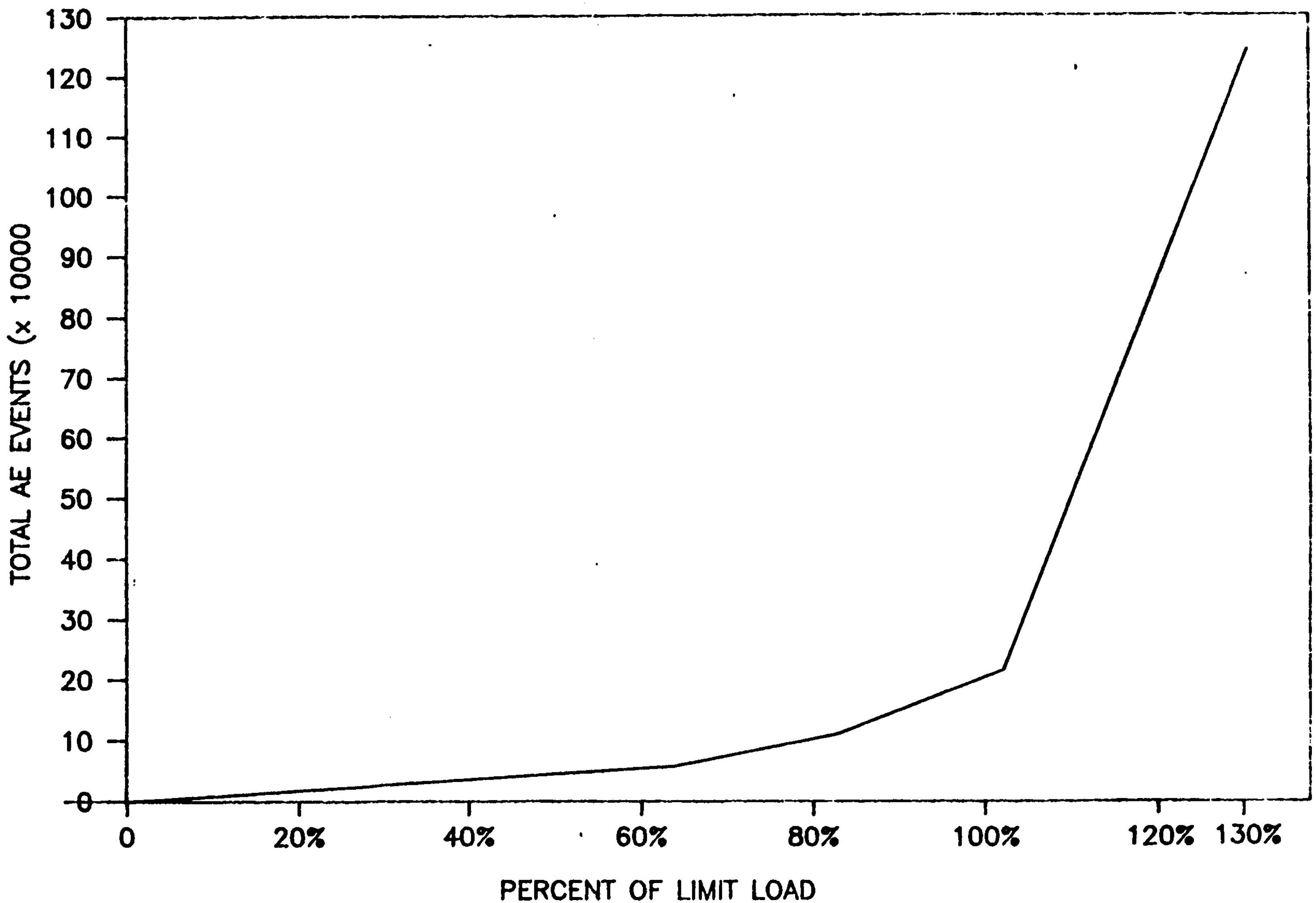

FIGURE 27. DR #4764, ITEM 1

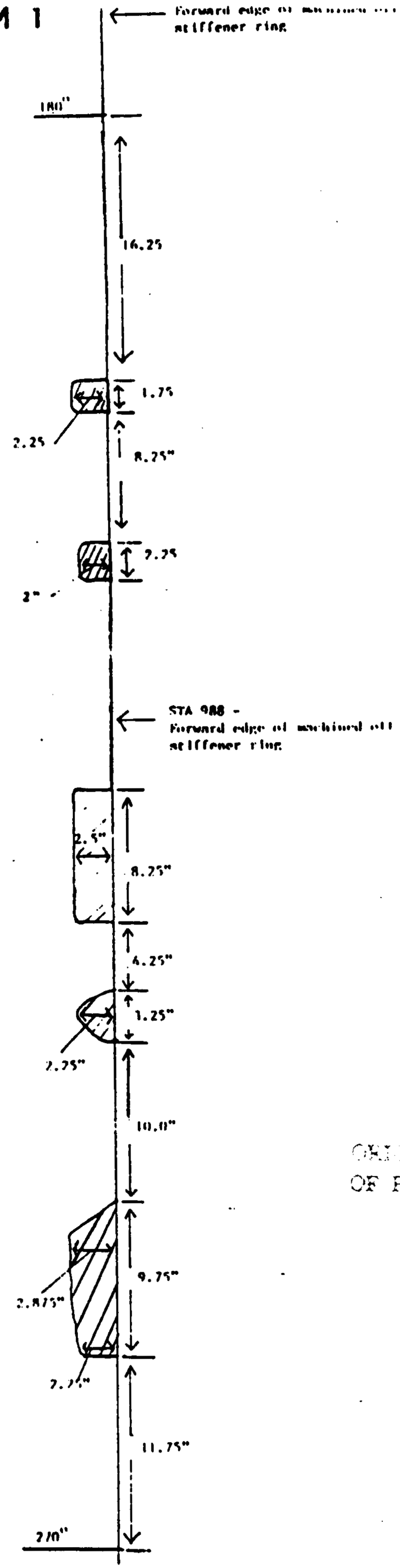

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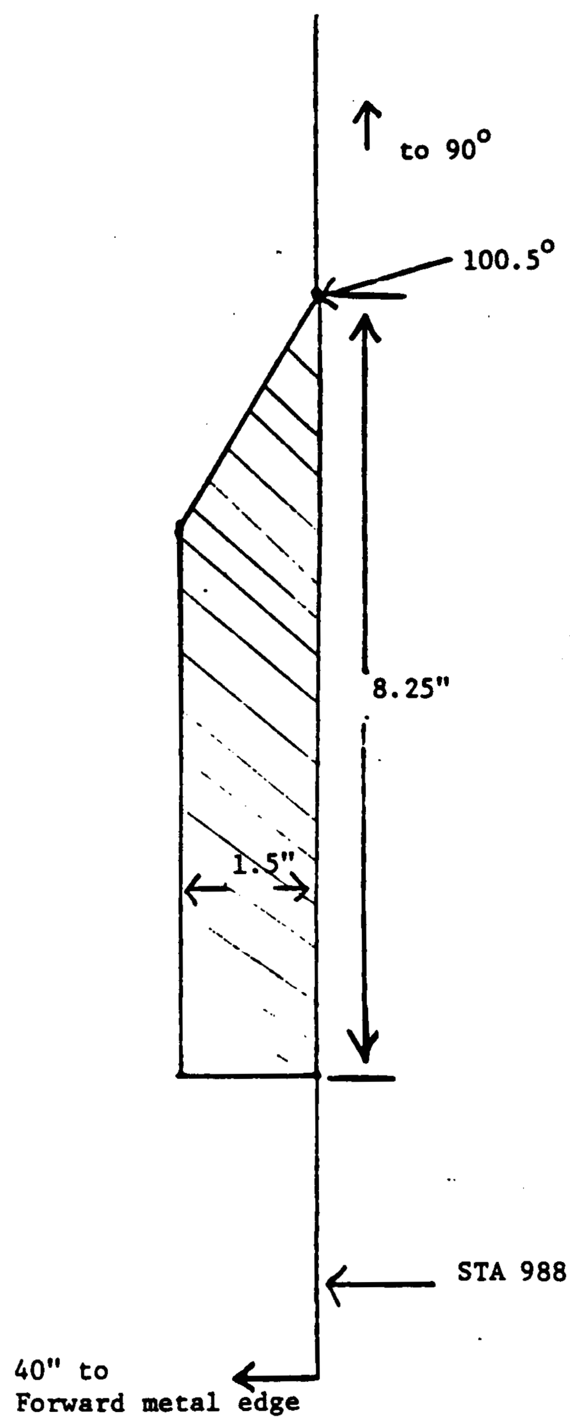
FIGURE 28. DR #4764. ITEM 2



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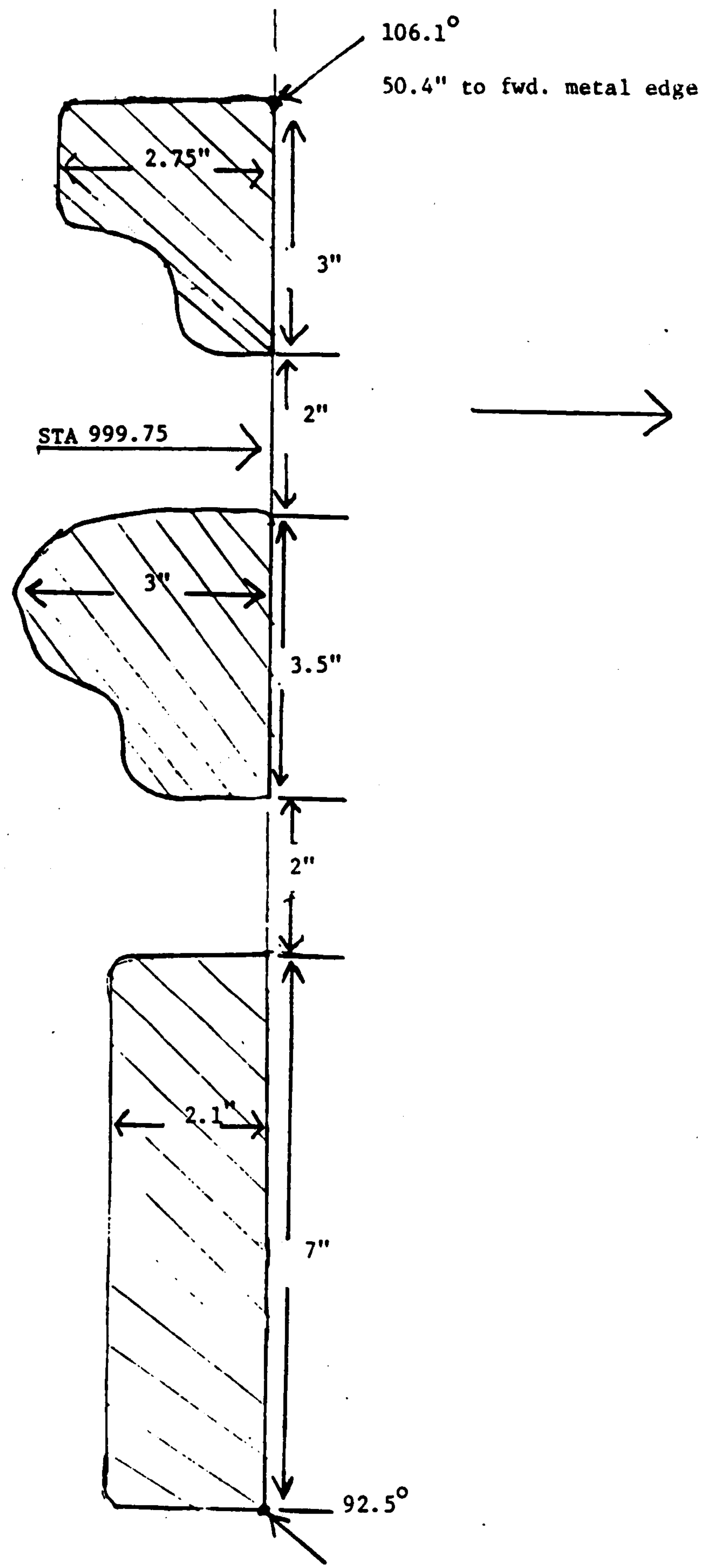
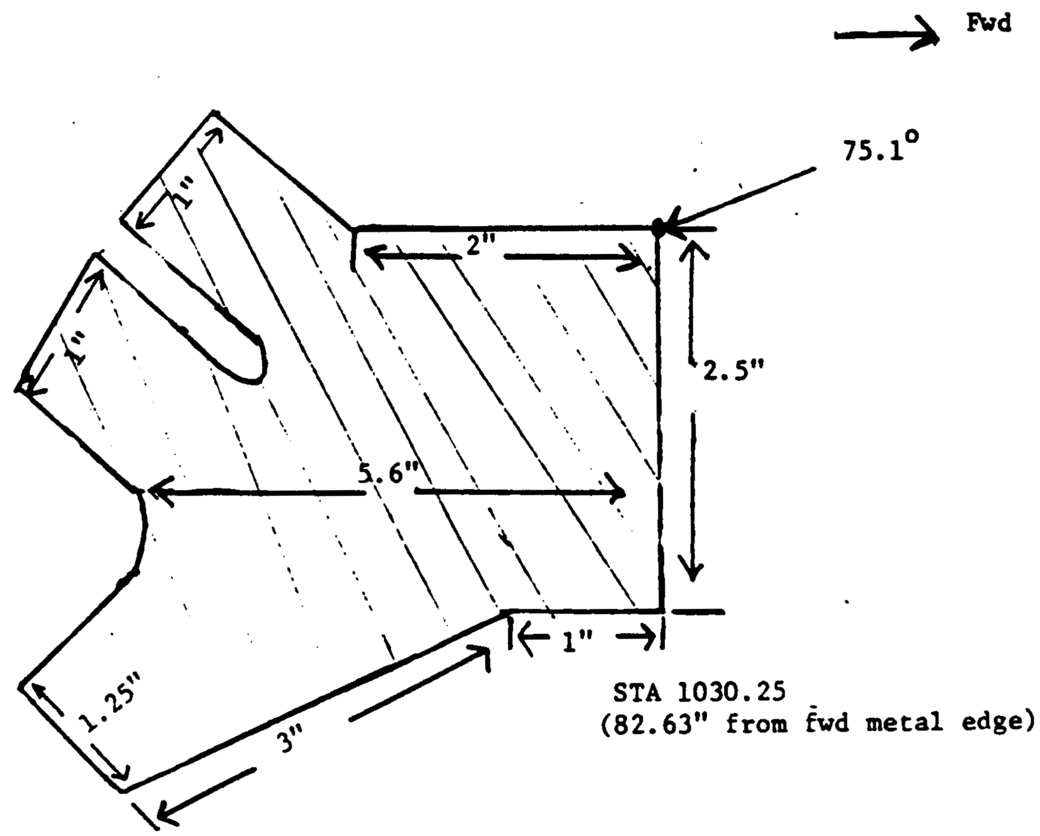


FIGURE 30. DR #4764, ITEM 4



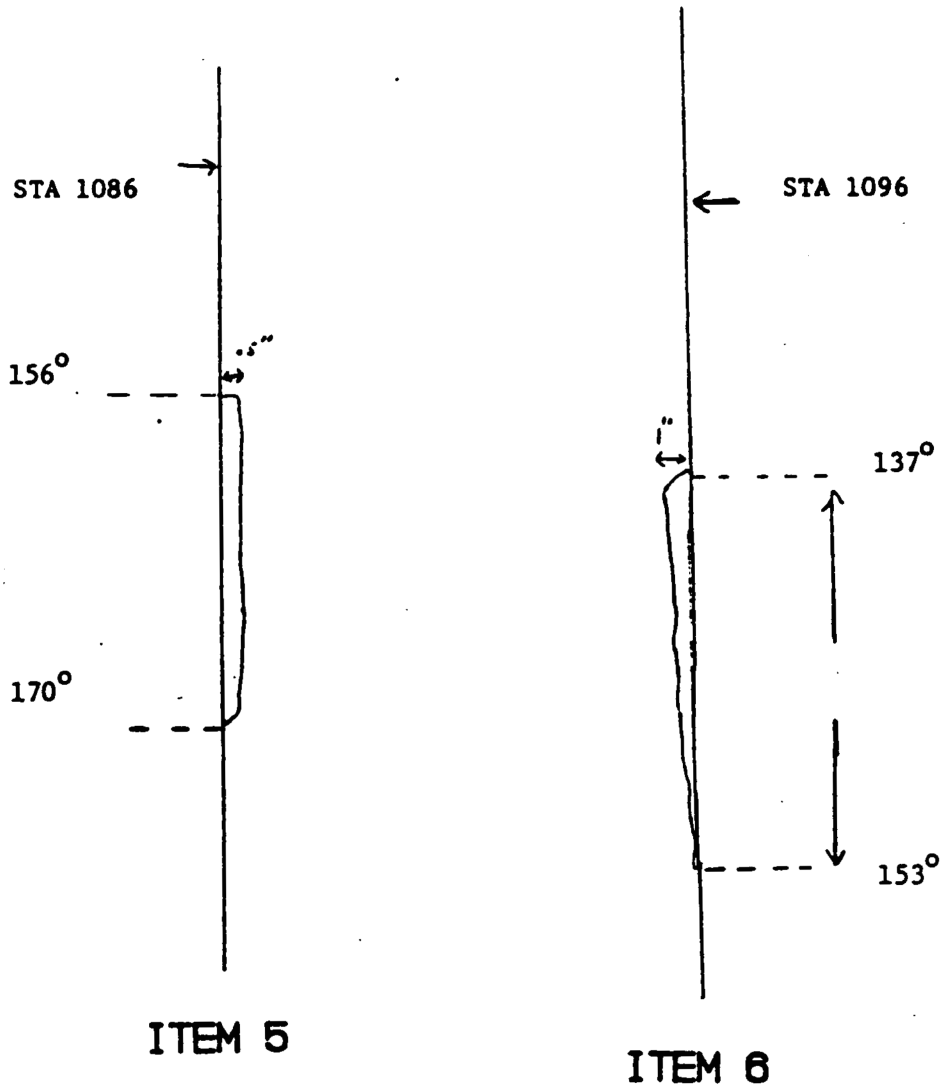
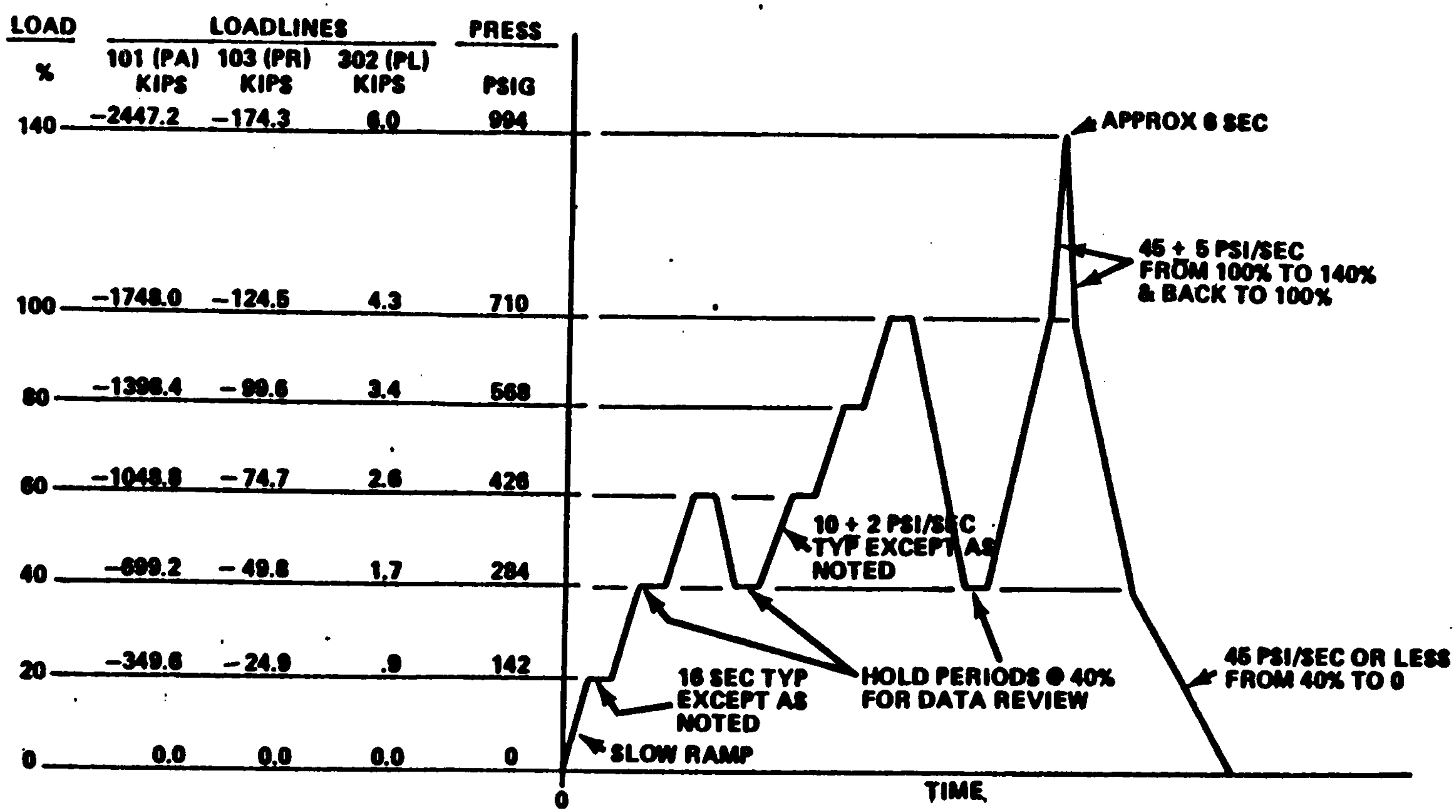


FIGURE 31. DR #4764

FIGURE 32. PROFILE 1 TEST SETUP 1, PHASE 8



NOTES:

1. + DESIGNATES TENSION ON LOAD CELLS
2. − DESIGNATES COMPRESSION ON LOAD CELLS
3. TRANSIENTS ARE APPLIED AS A HAVERSINE $\frac{(1 - \text{COSINE})}{2}$
4. DESCRETE SCANS WILL BE MADE AT 0, 20, 40, 60, 40, 60, 80, 100, 40 PERCENTS
5. APPLICATION & RELEASE RATES OF PA, PR, PL WILL BE IN PROPORTION TO PRESSURE

FIGURE 33. TOTAL EVENTS PER SENSOR LOCATION
TEST PHASE 8

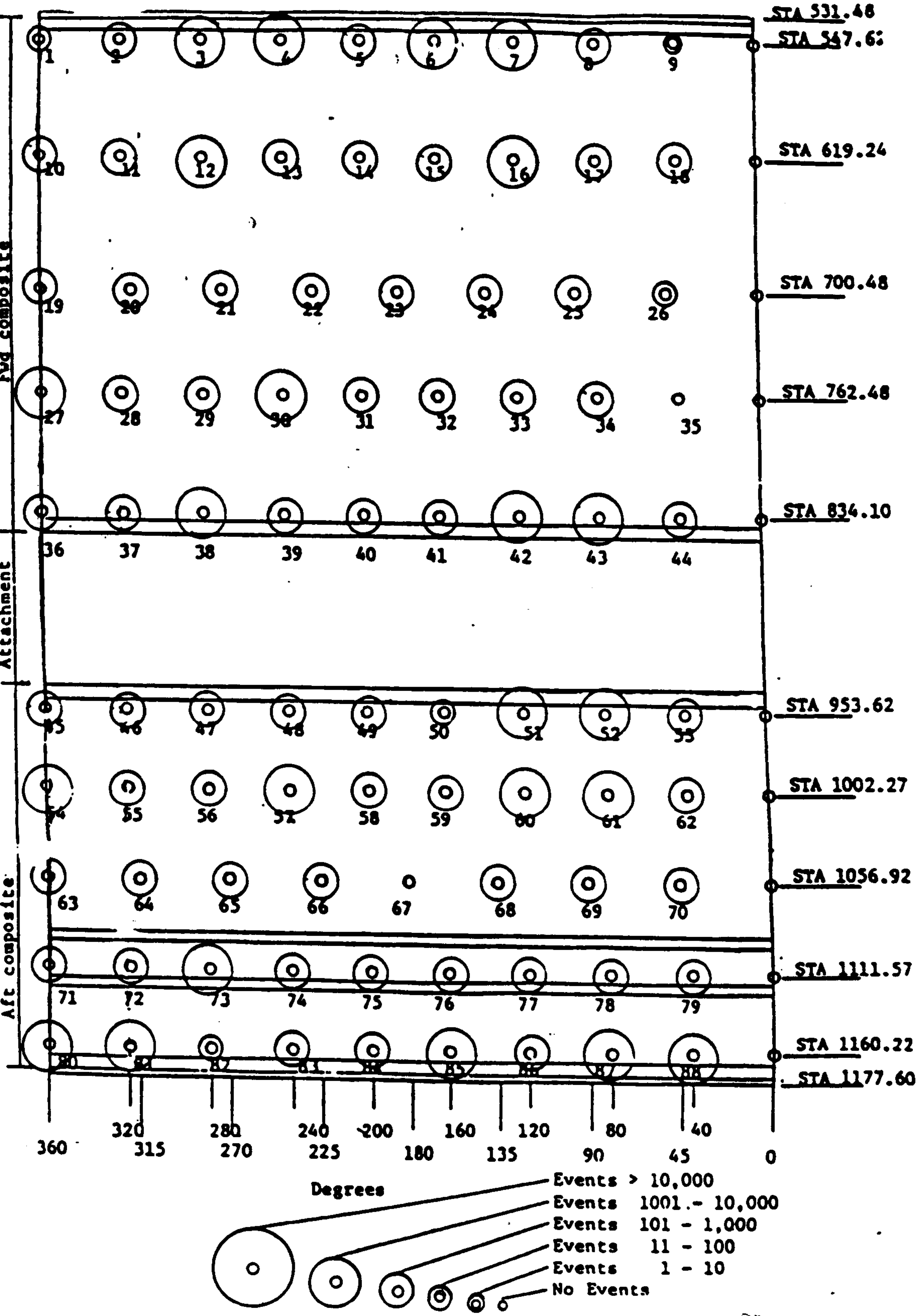


TABLE 1
PHASE 9C NDT CHRONOGICAL TEST RECORD

NUMBER OF TEST LOAD	TEST DATE	EVENT	REMARKS
1	5-16-85	LOADED TO 60% LIMIT LOAD	TEST STOPPED DUE TO SIU PROBLEM; NO DEFECT GROWTH
2	5-17-85	LOADED TO 90% LIMIT LOAD	TEST STOPPED DUE TO HIGH AE ACTIVITY. 2 DELAMINATIONS FOUND IN AFT SEGMENT BY PULSE ECHO
3	7-2-85	LOADED TO 90% LIMIT LOAD	MINOR DEFECT GROWTH DETECTED BY AE AND PULSE ECHO.
4	7-10-85	LOADED TO 90% LIMIT LOAD	TEST STOPPED DUE TO FAILURE OF LOAD LINE.
5	7-16-85	LOADED TO 125% LIMIT LOAD	AE DISPLAYS SIGNIFICANT DEFECT GROWTH DURING LOADING. PULSE ECHO MAPS LARGE GROWTH.
6	7-24-85	LOADED TO 129% LIMIT LOAD, FAILURE IN AFT SEGMENT.	AE SHOWS DEFECT GROWTH IN FAILURE LOCATION.

FIGURE 34. STA-2 PHASE 9C–1ST LOADING

APPLIED LOAD VS. TIME

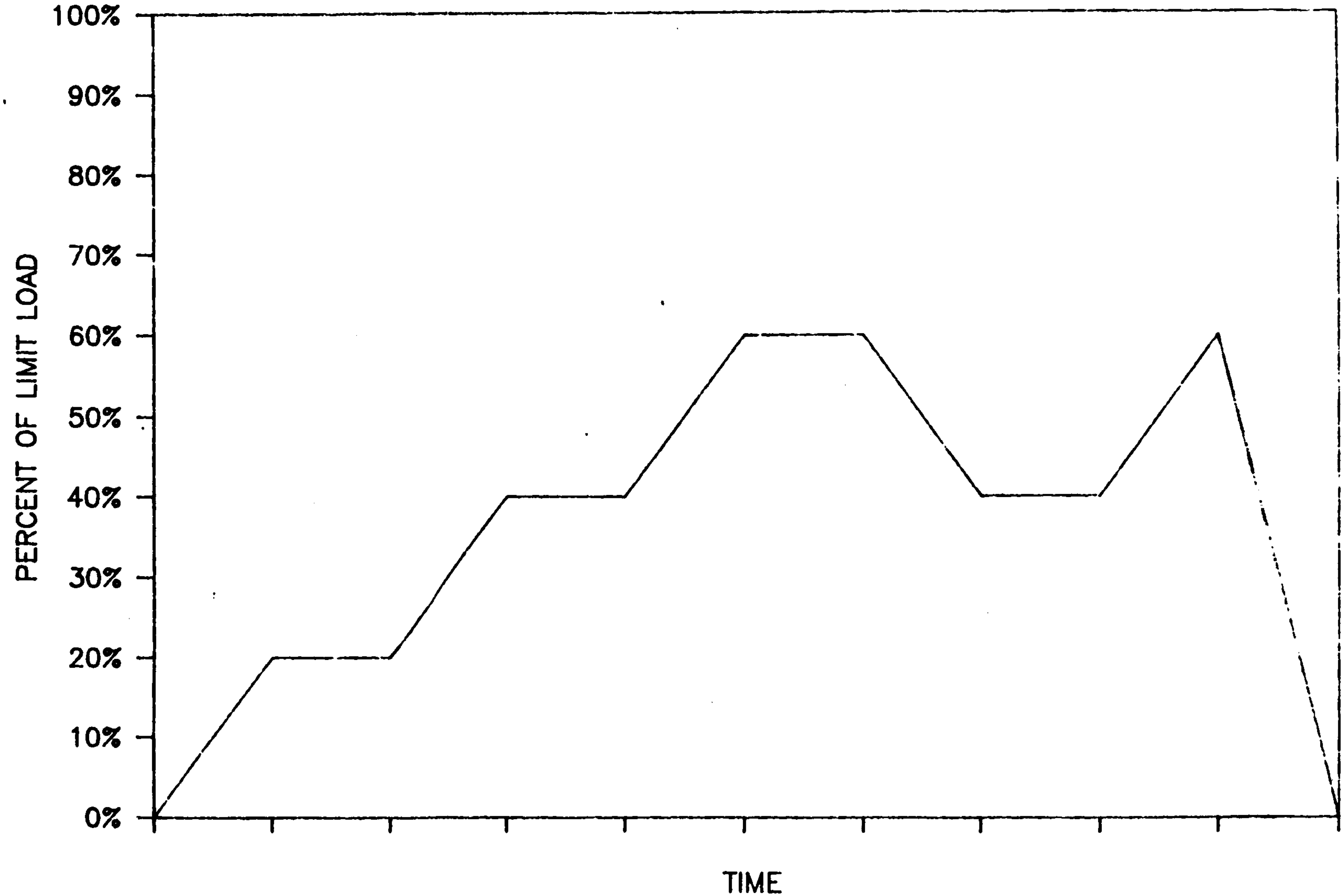


FIGURE 35. STA-2 PHASE 9C-2ND LOADING
APPLIED LOAD VS. TIME

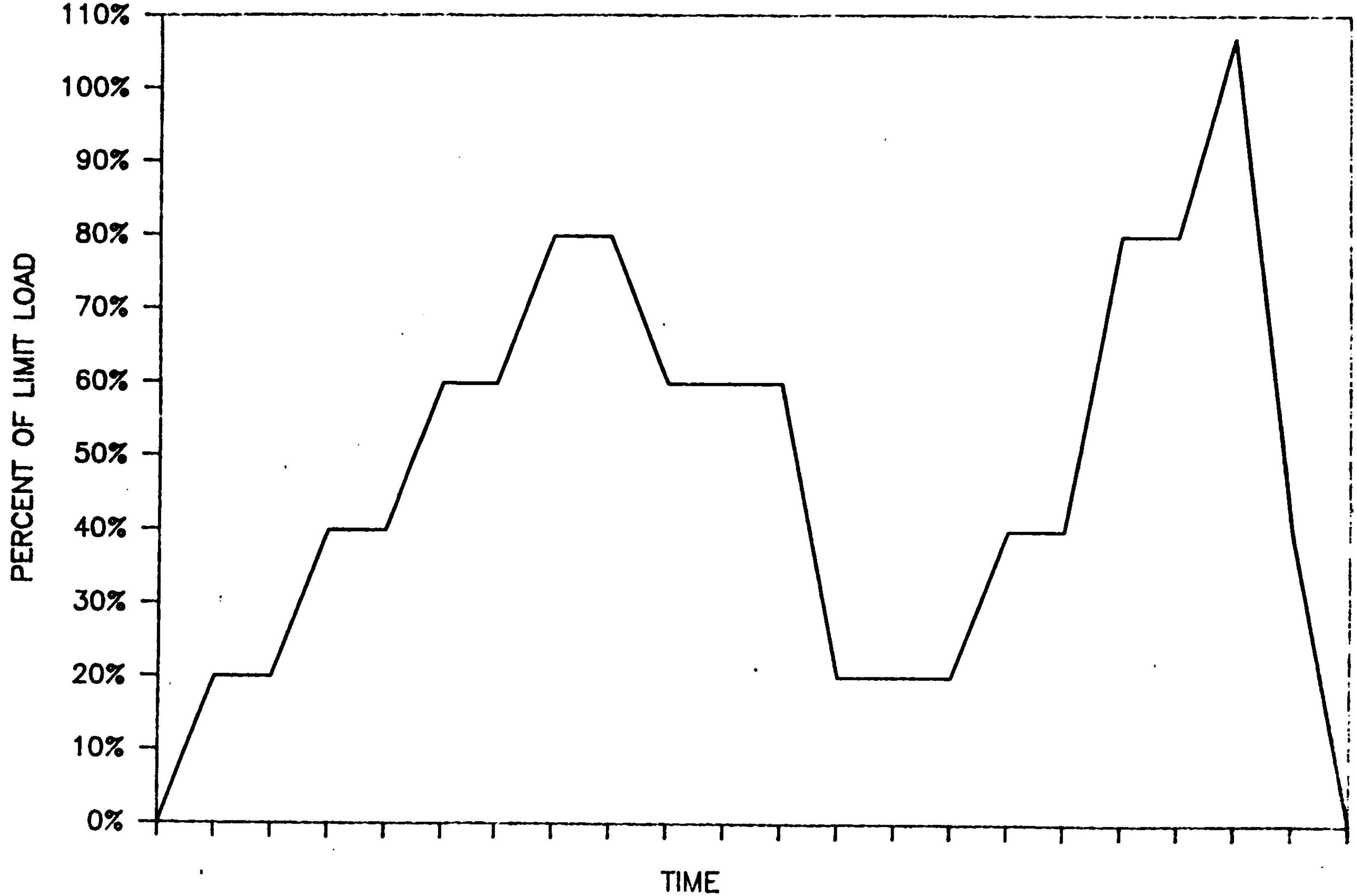


FIGURE 36. STA-2 PHASE 9C-3RD LOADING

APPLIED LOAD VS. TIME

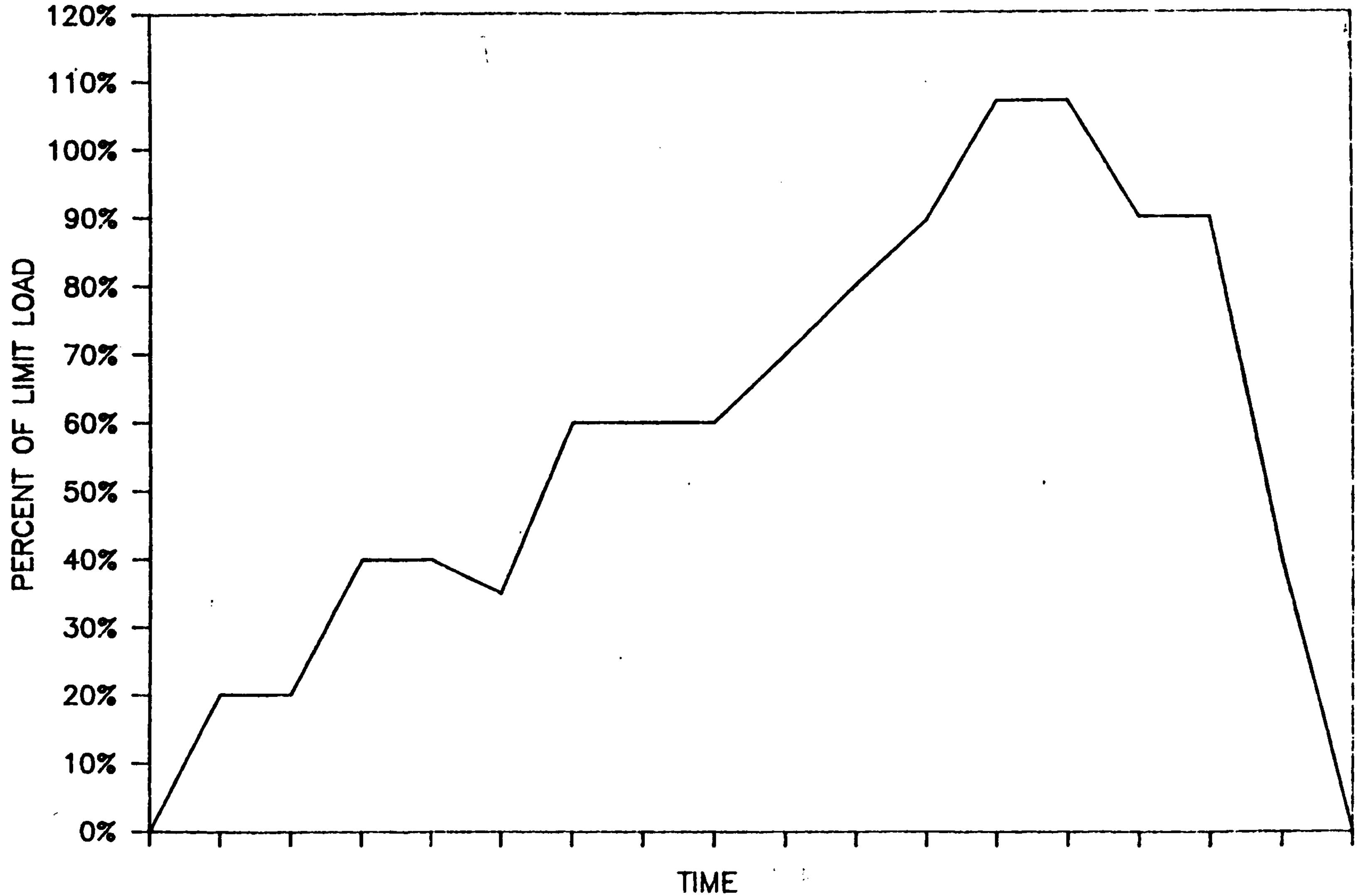


FIGURE 37. STA-2 PHASE 9C-4TH LOADING

APPLIED LOAD VS. TIME

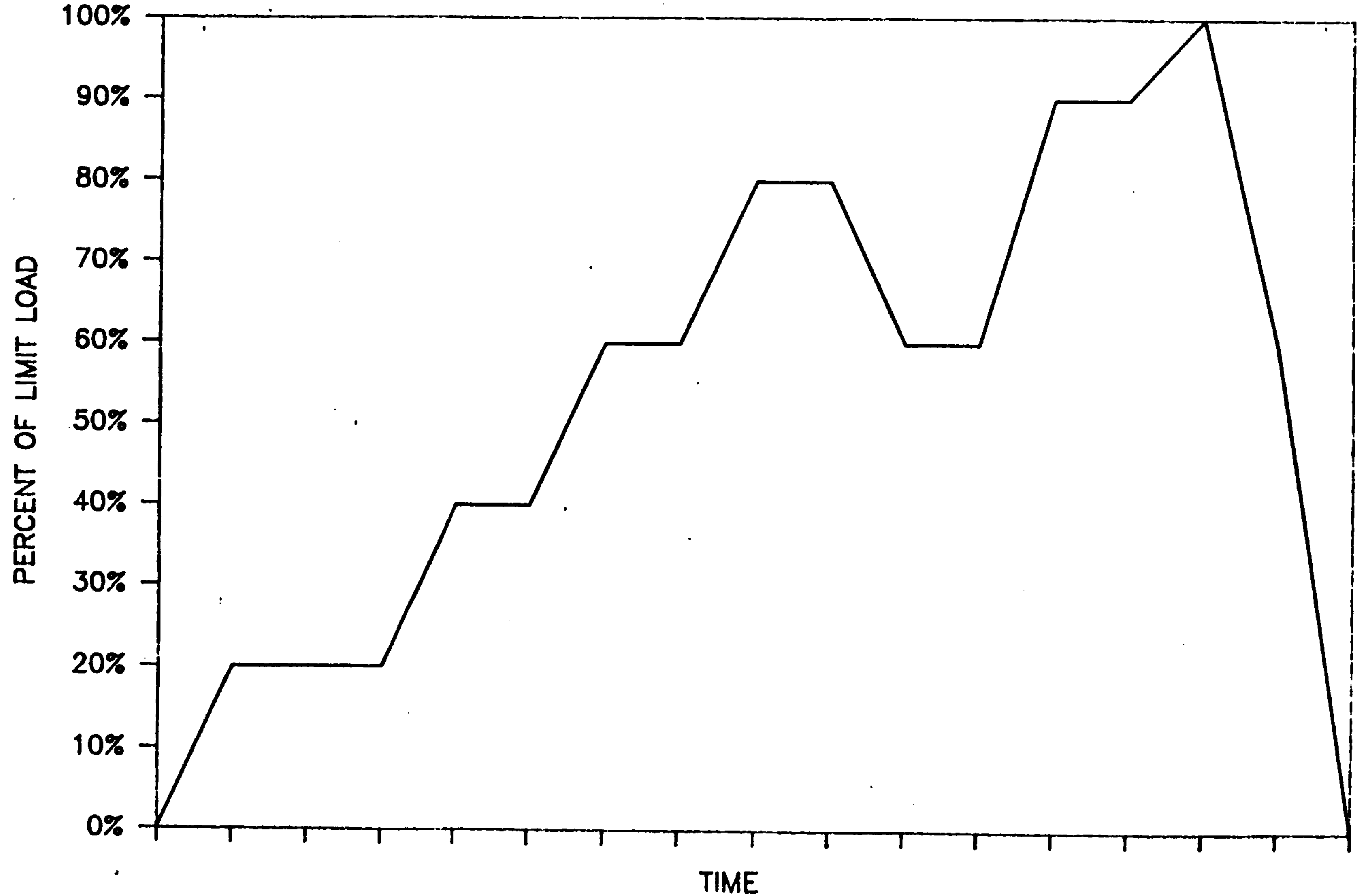


FIGURE 38. STA-2 PHASE 9C-5TH LOADING

APPLIED LOAD VS. TIME

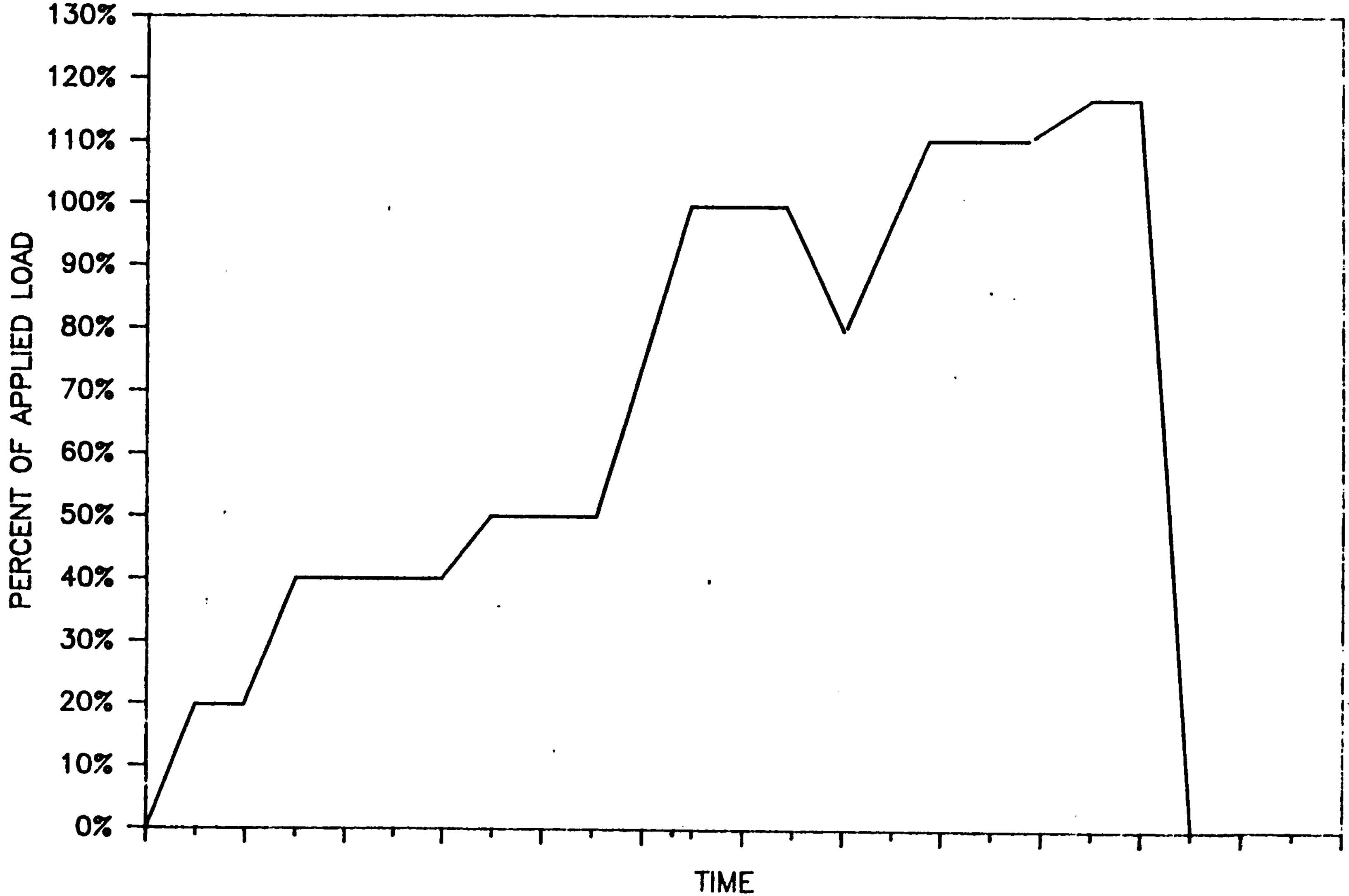


FIGURE 39. STA-2 PHASE 9C-6TH LOADING

APPLIED LOAD VS. TIME

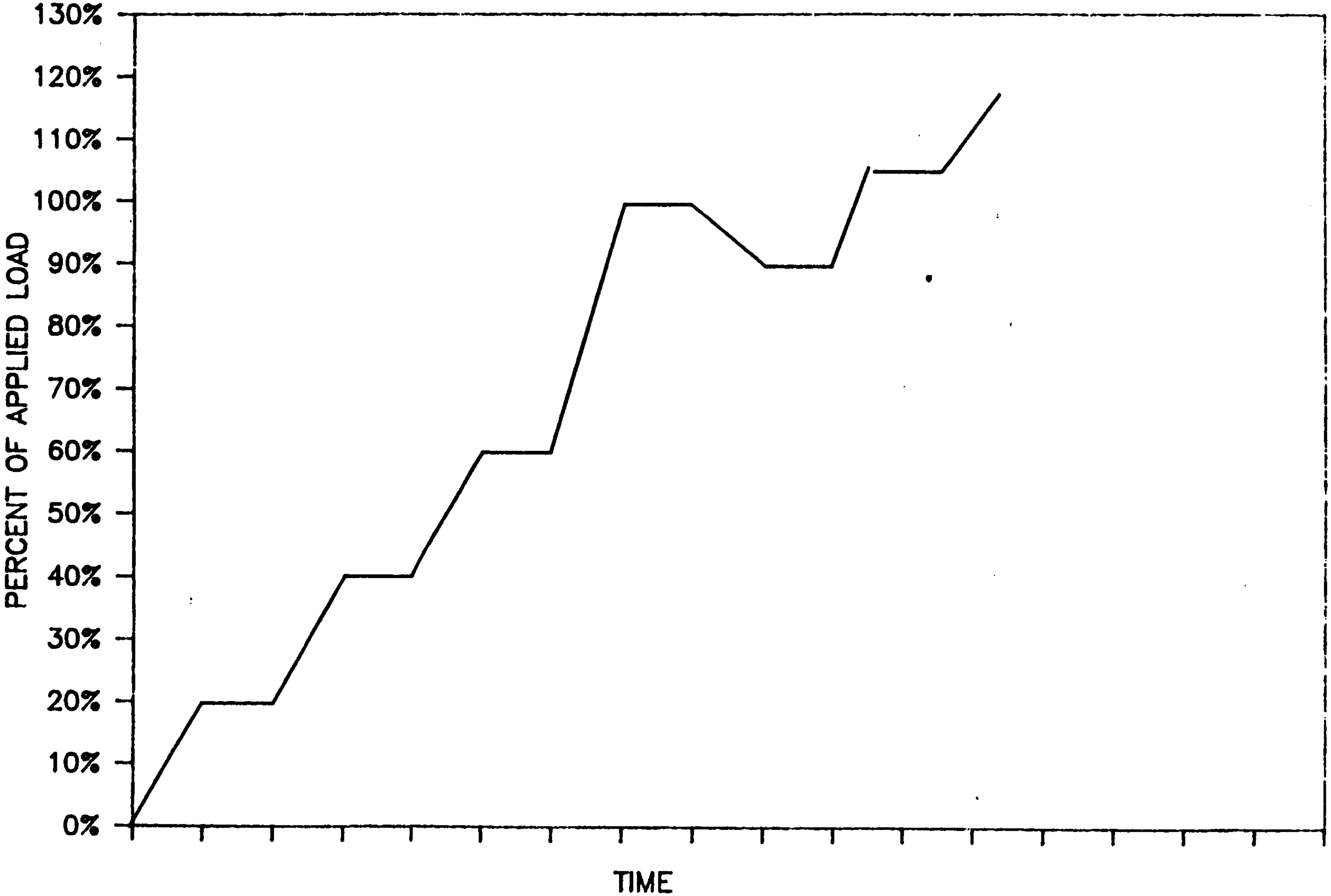


FIGURE 40. STA-2 PHASE 9C-2ND LOADING

CUMULATIVE EVENTS VS. LOAD

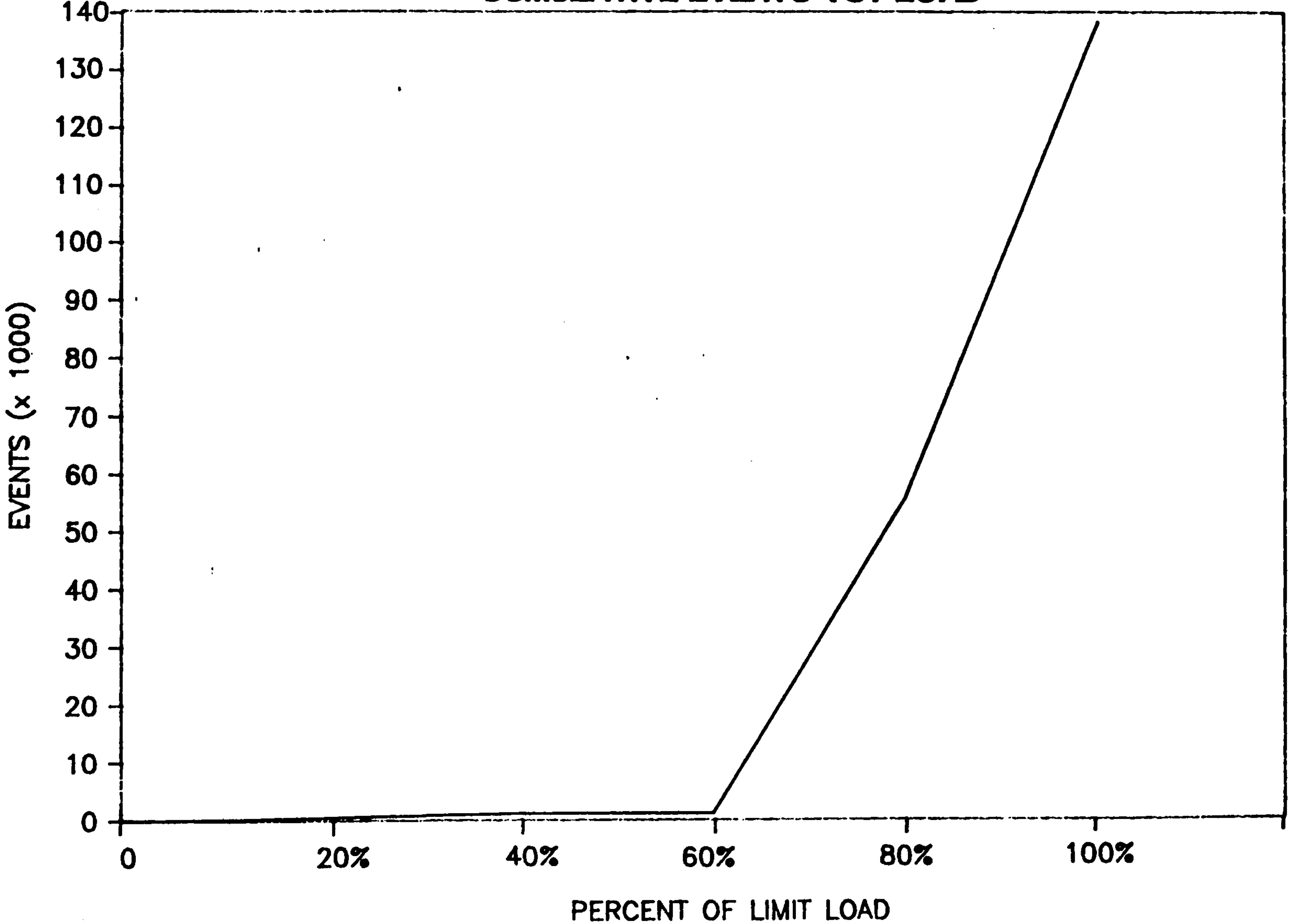


FIGURE 41. TOTAL EVENTS DURING LOAD HOLD
PER SENSOR LOCATION
PHASE 9C- 2ND LOADING

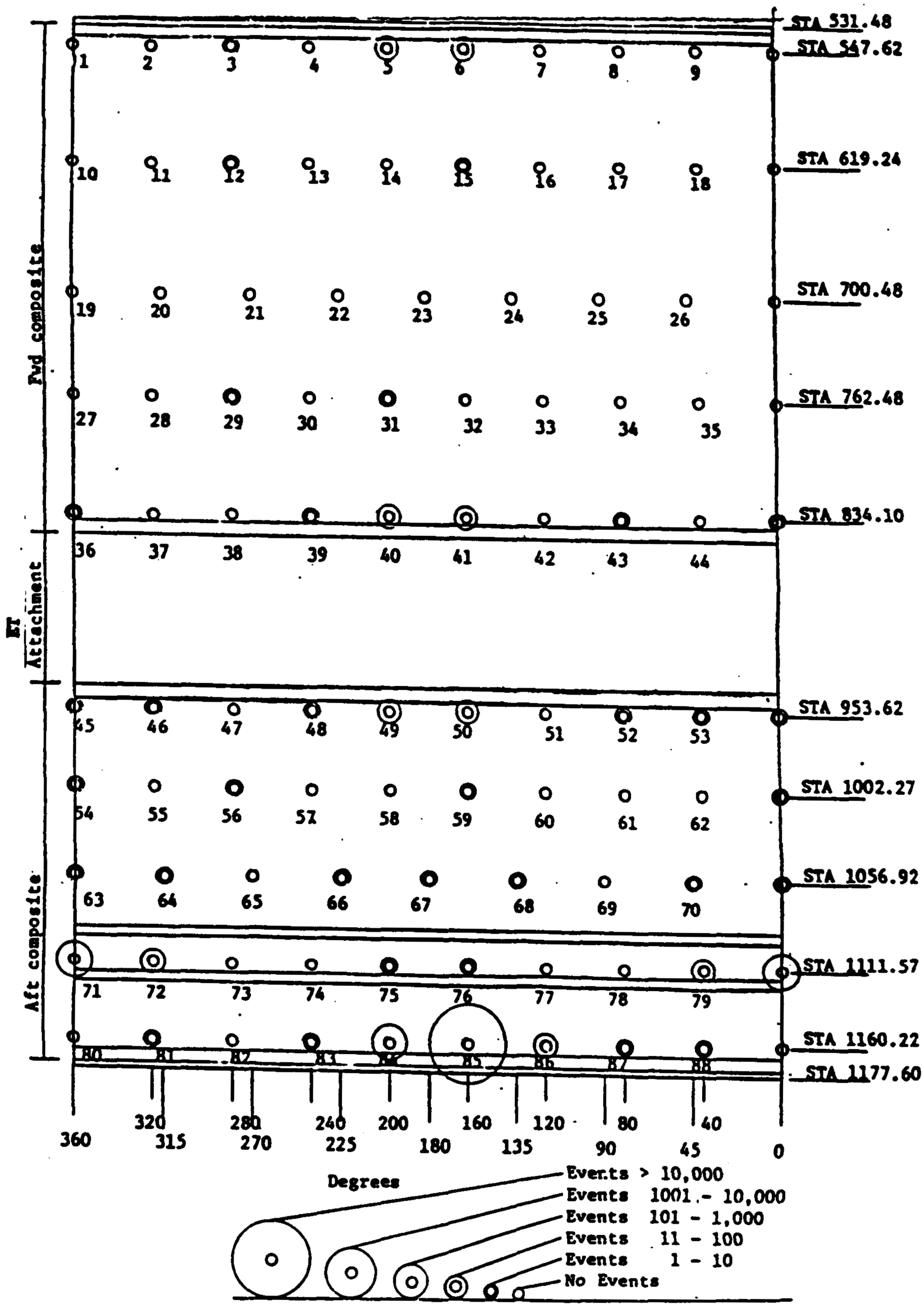


FIGURE 42. PULSE ECHO INSPECTION RESULTS

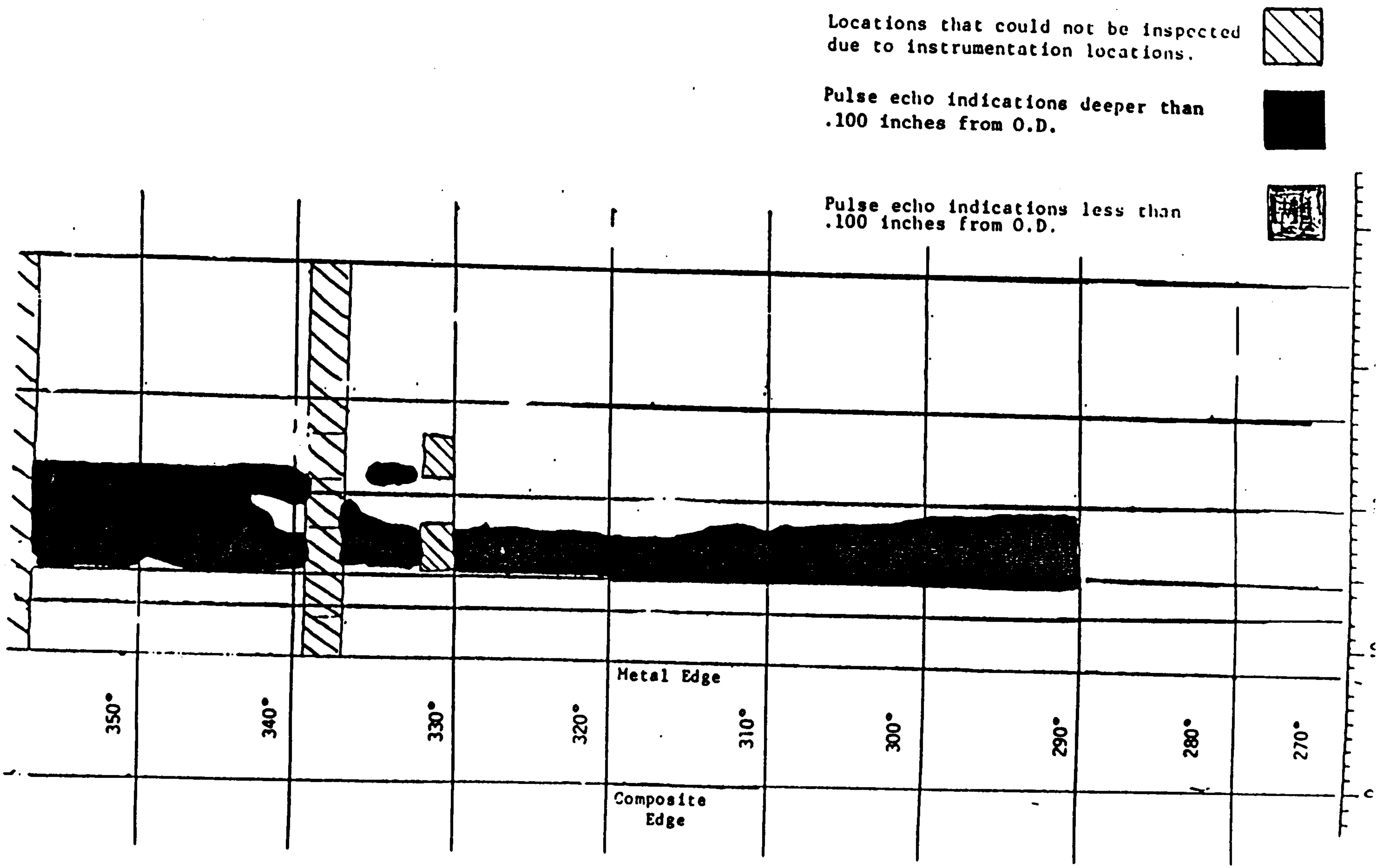


FIGURE 43. PULSE ECHO INSPECTION RESULTS
AFT SEGMENT-AFT TRANSITION REGION

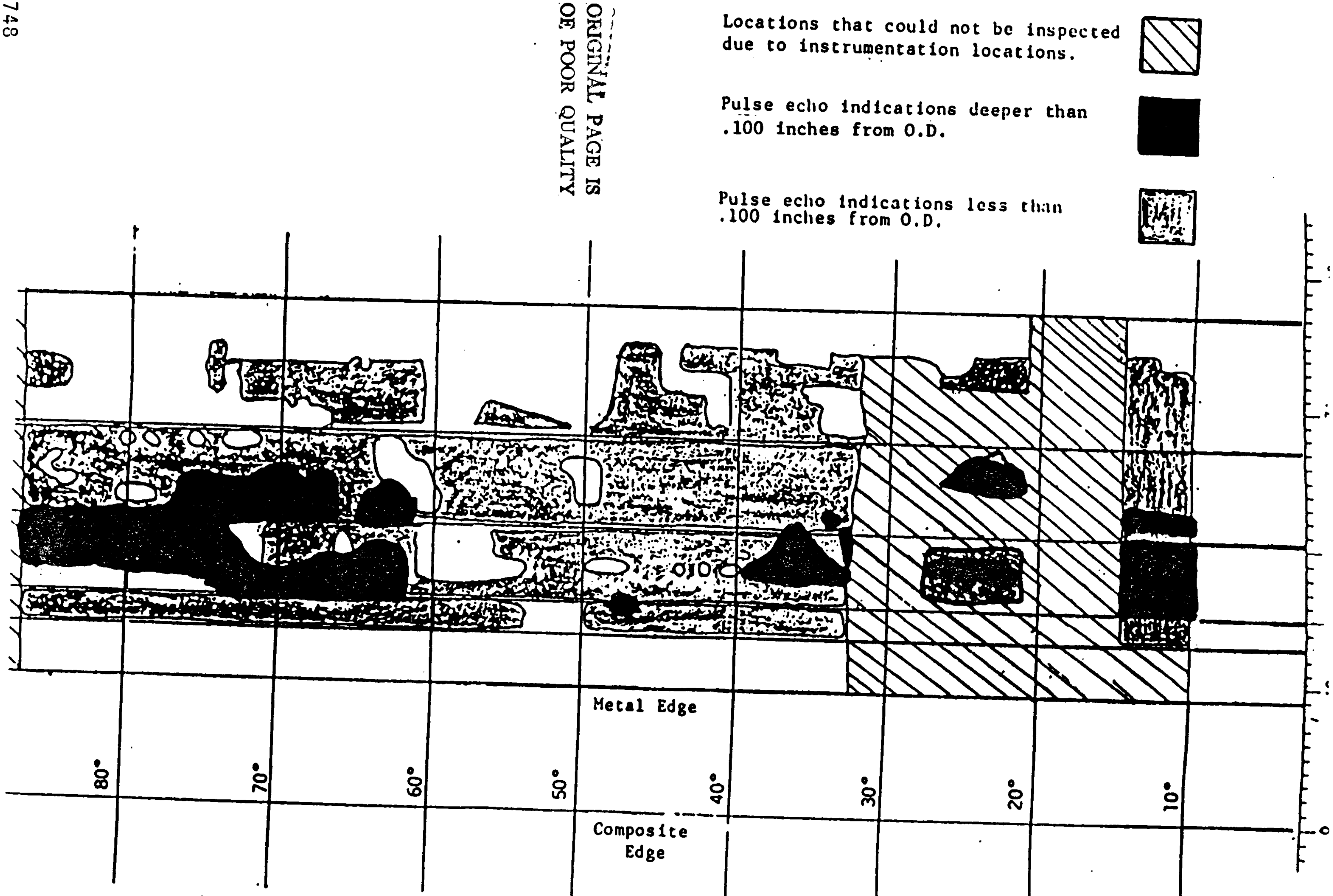


FIGURE 44. PULSE ECHO INSPECTION RESULTS AFT SEGMENT-AFT TRANSITION REGION

Locations that could not be inspected due to instrumentation locations.

Pulse echo indications deeper than .100 inches from O.D.

Pulse echo indications less than .100 inches from O.D.

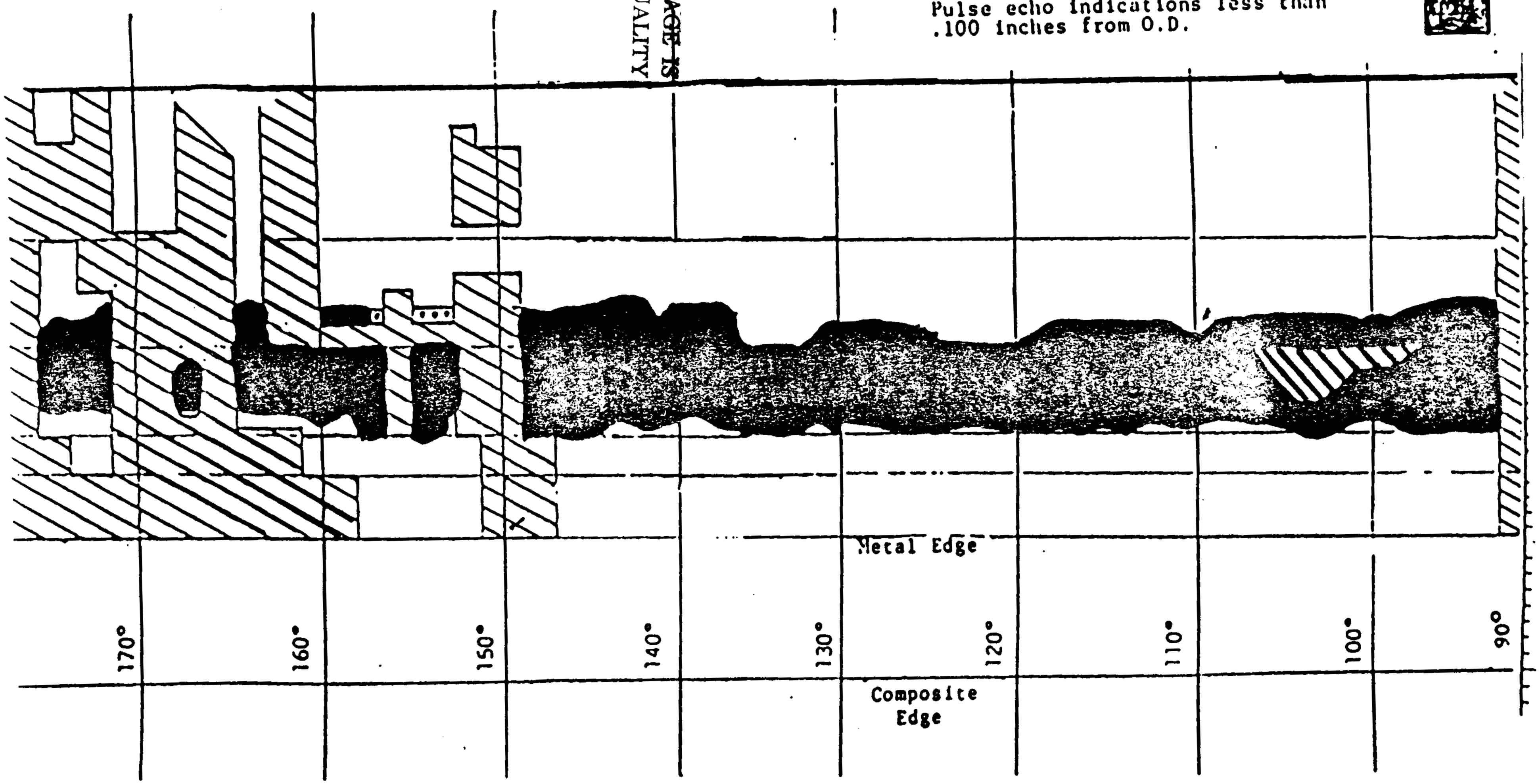
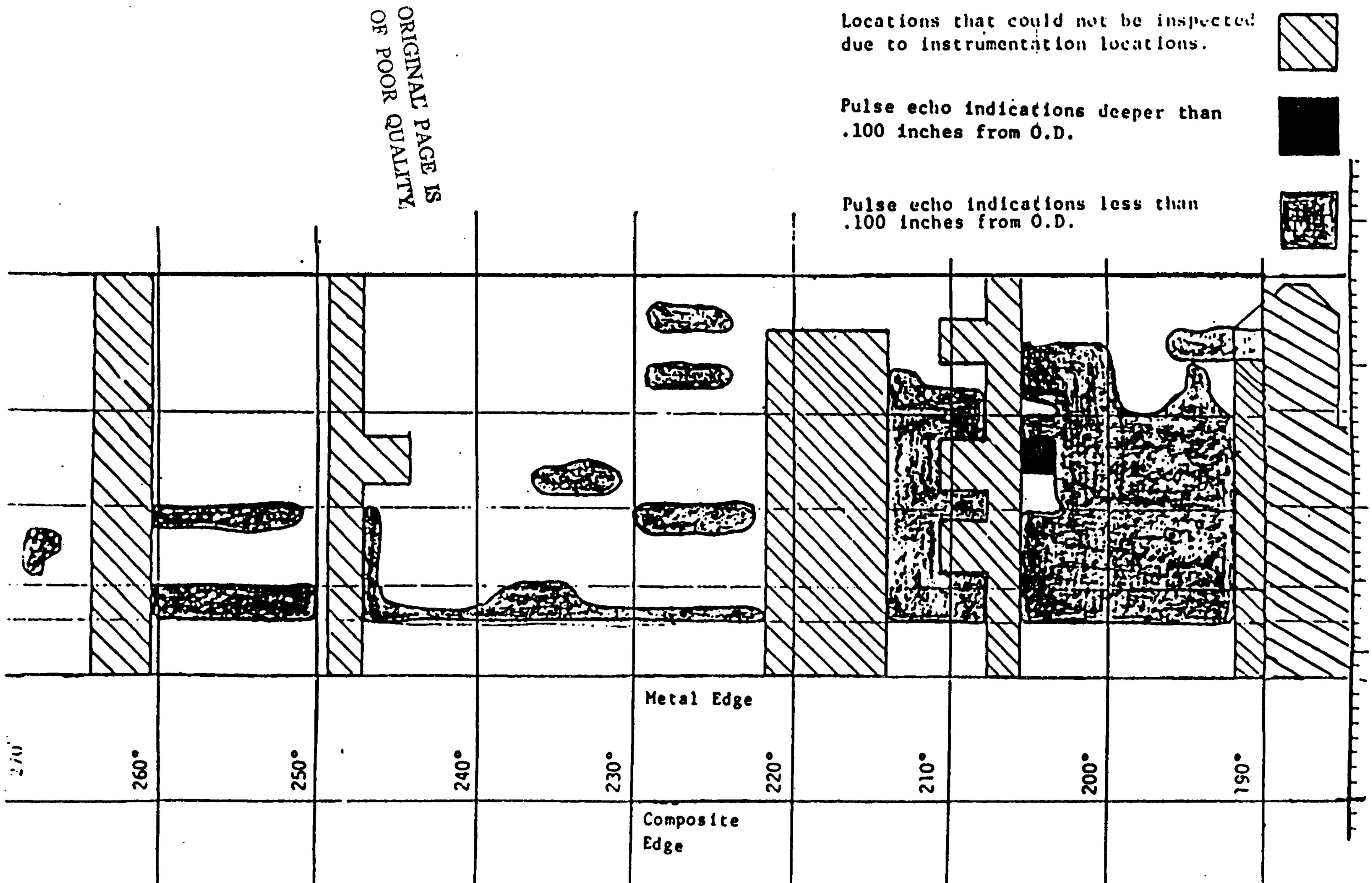


FIGURE 45. PULSE ECHO INSPECTION RESULTS AFT SEGMENT-AFT TRANSITION REGION



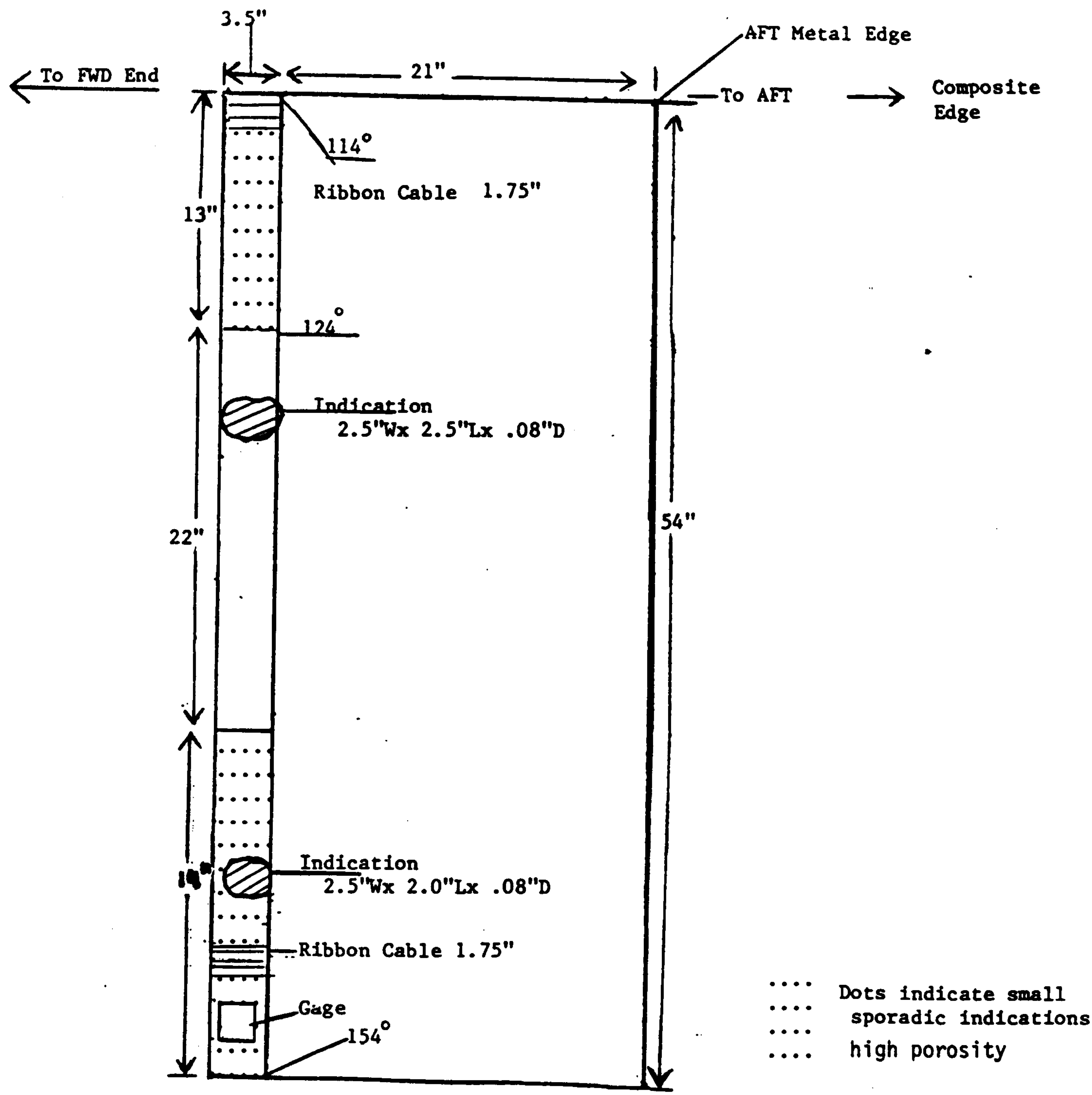
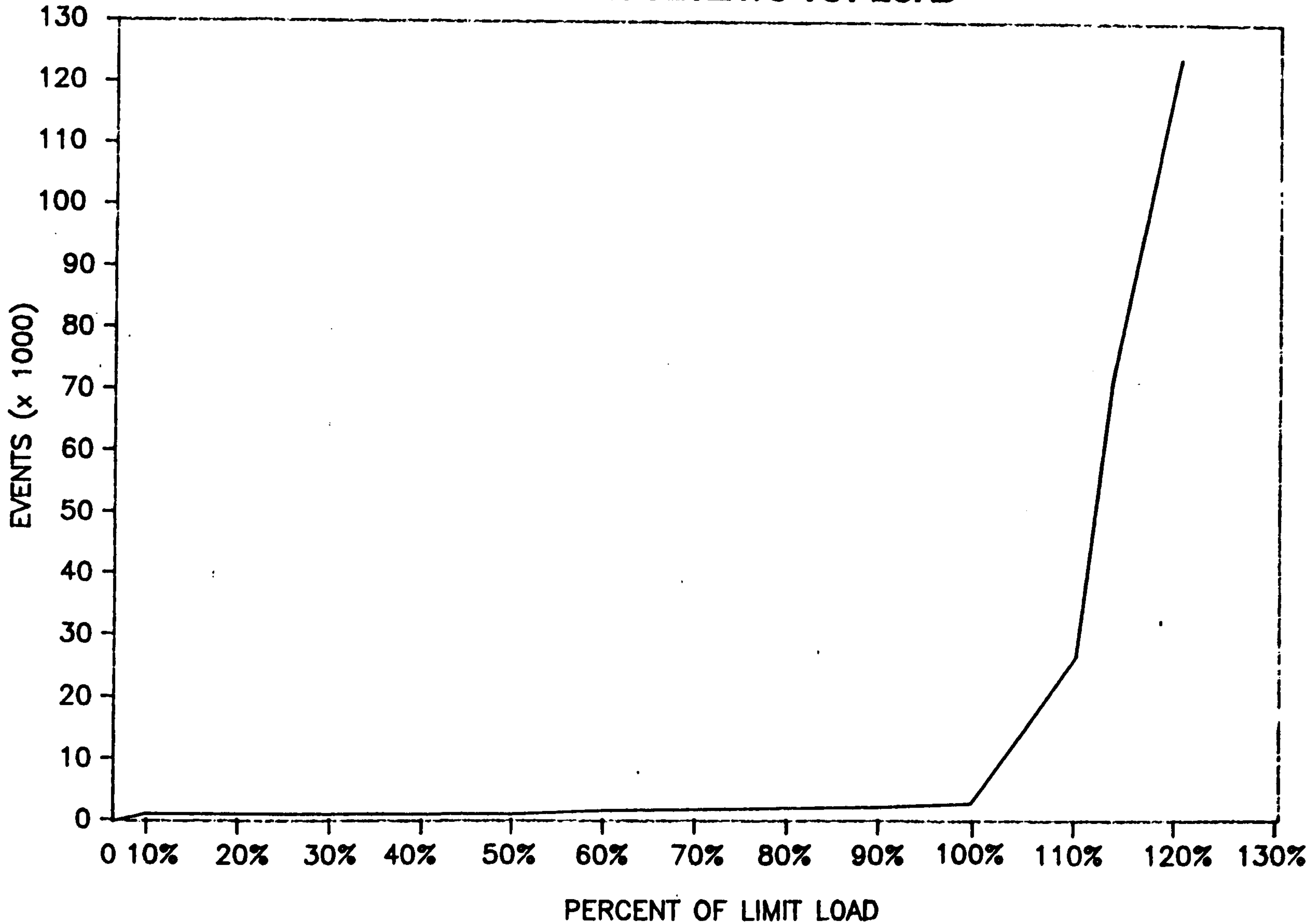


FIGURE 46. PULSE ECHO INSPECTION RESULTS
AFT SEGMENT-AFT TRANSITION REGION

FIGURE 47. STA-2 PHASE 9C–5TH LOADING

CUMULATIVE EVENTS VS. LOAD



STA-2 AFT SEGMENT DELAMINATION GROWTH DURING TESTING

Delamination after 117-percent load test and after failure at 118.4-percent load test

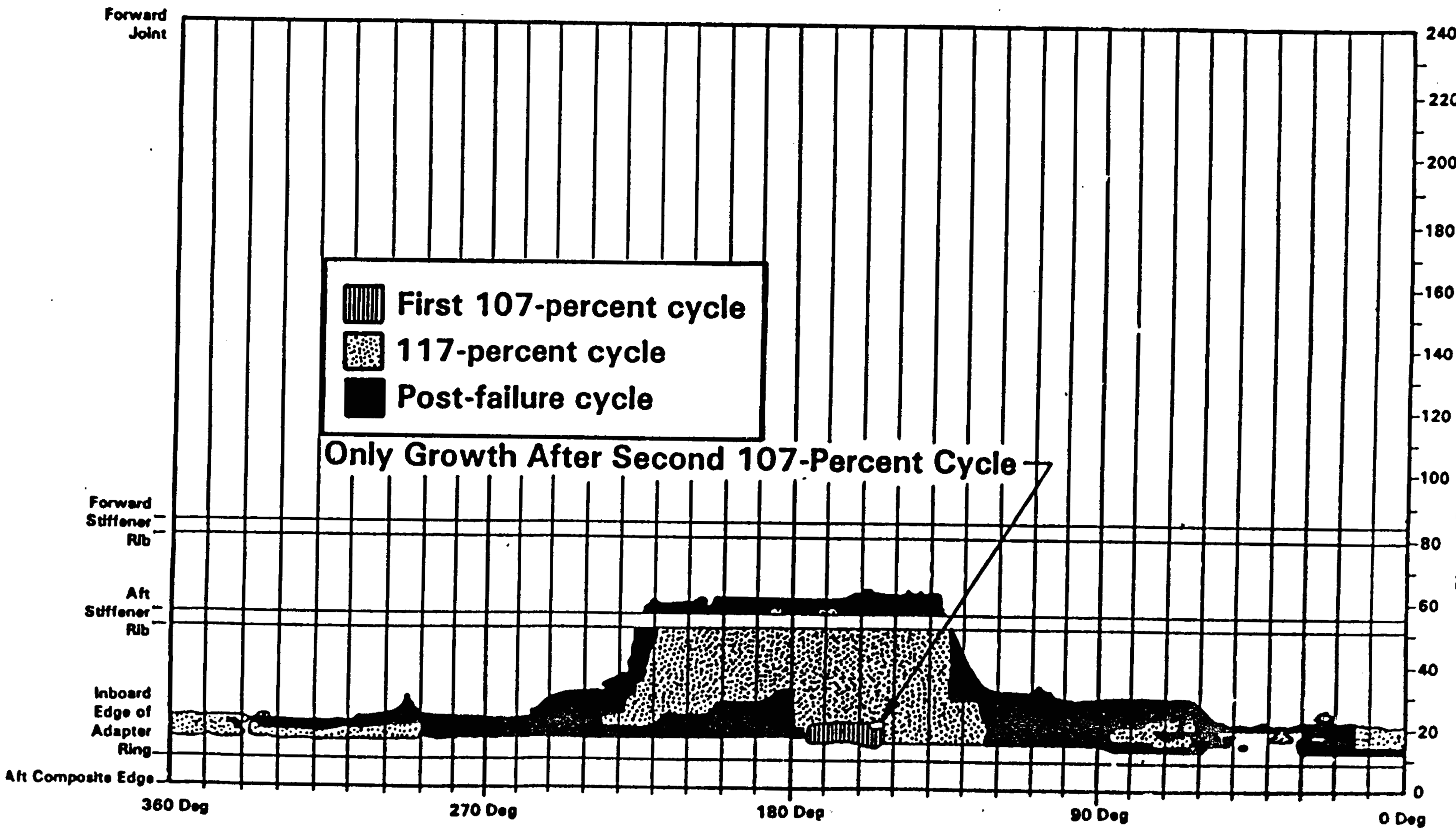


FIGURE 48.

FIGURE 49 AE SENSOR LOCATIONS IN DEFECT REGION

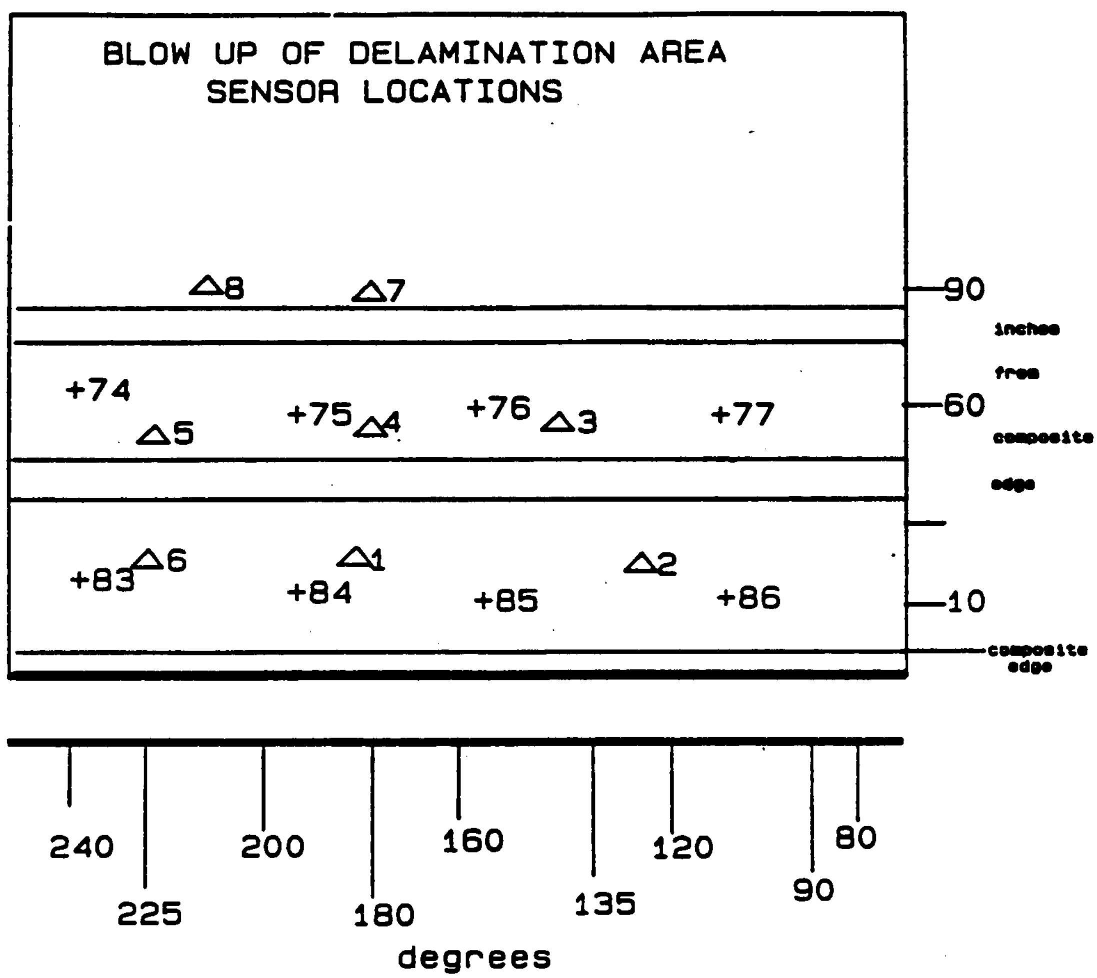


FIGURE 50. STA-2 PHASE 9C-6TH LOADING
CUMULATIVE EVENTS VS. LOAD

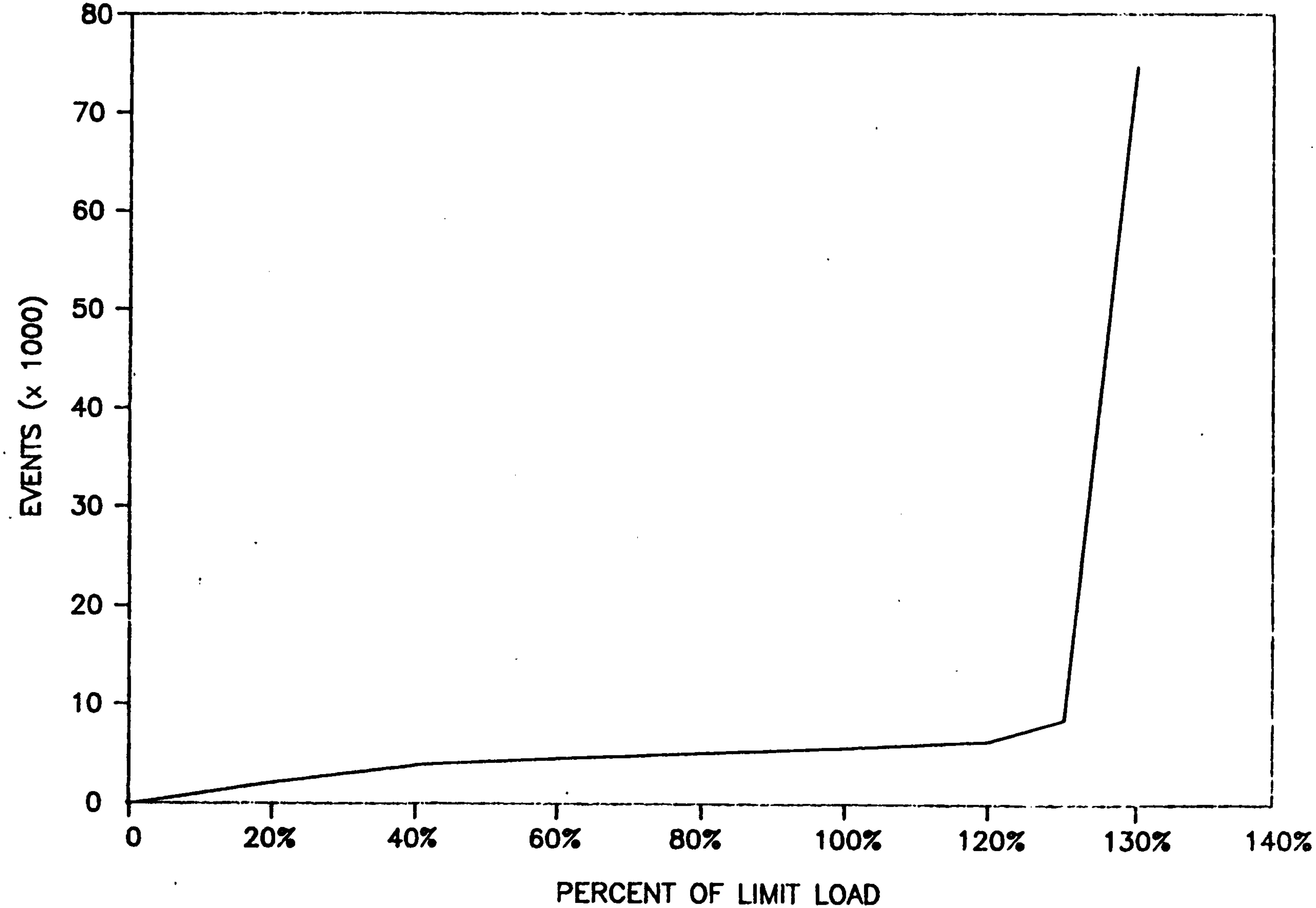


FIGURE 51. TOTAL EVENTS AT EACH SENSOR LOCATION IN DEFECT REGION

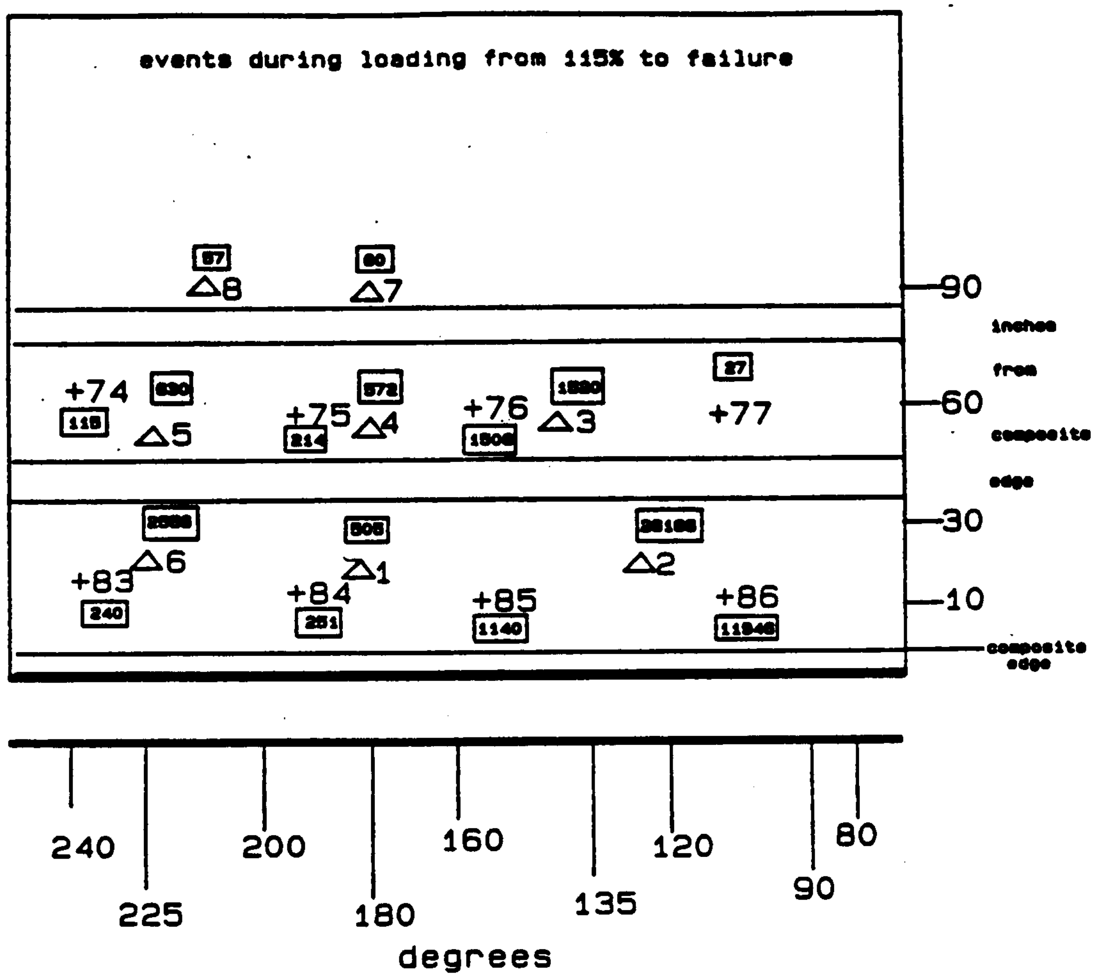


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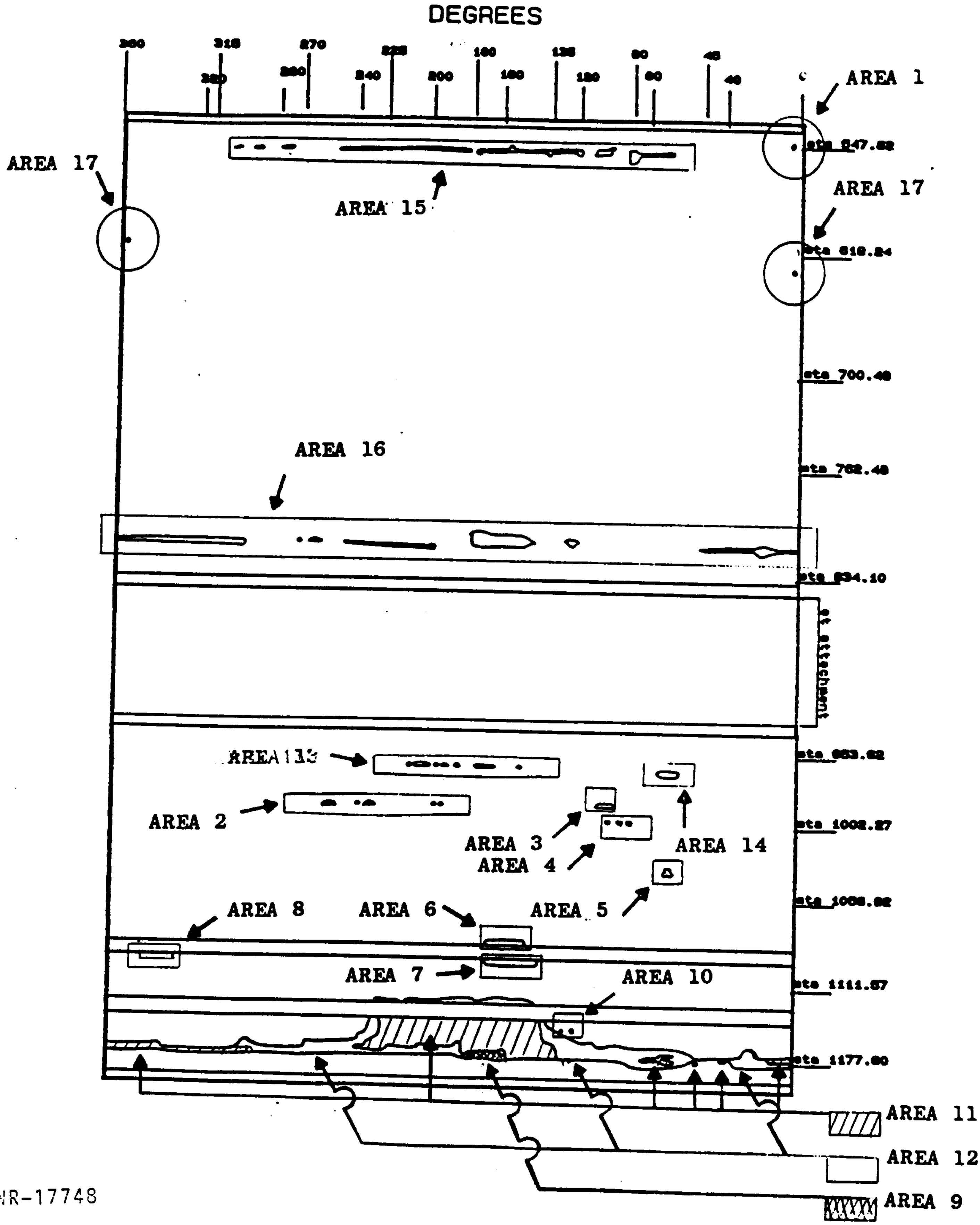
FIGURE 52. POST FAILURE PULSE ECHO INSPECTION



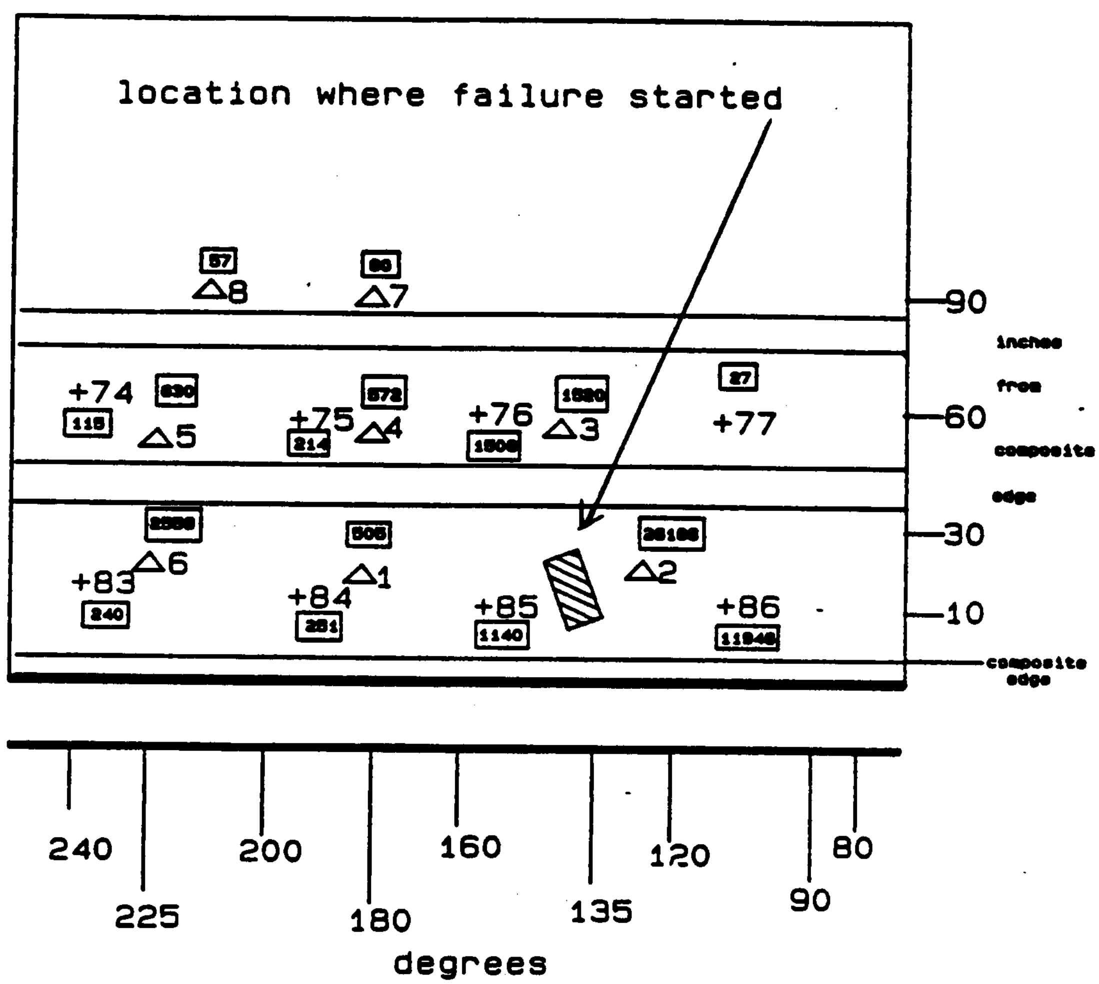


FIGURE 53. FAILURE LOCATION

FIGURE 54. FAILURE LOCATION

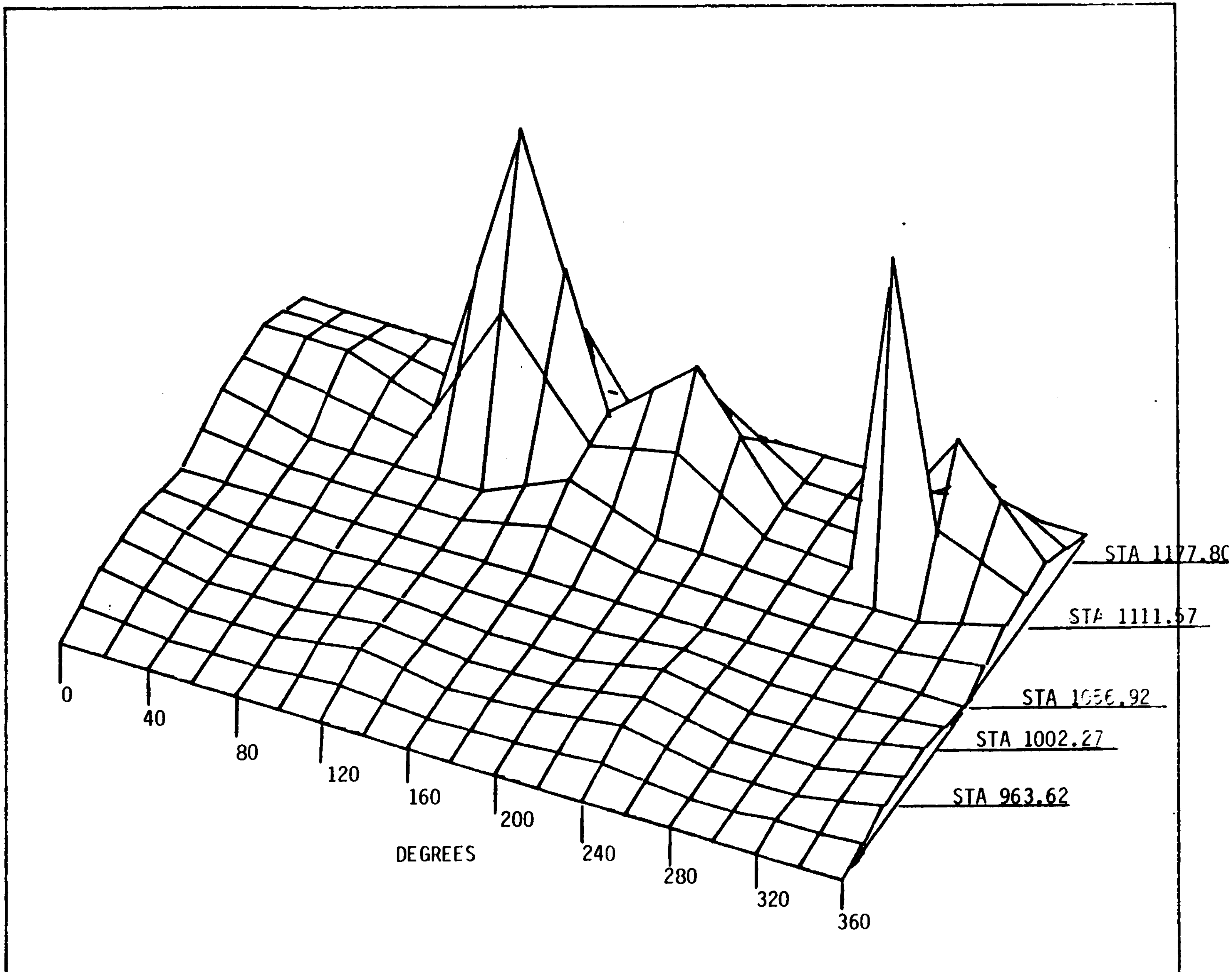


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FIGURE 55. LOCATIONS OF SELECTED NDT SAMPLES

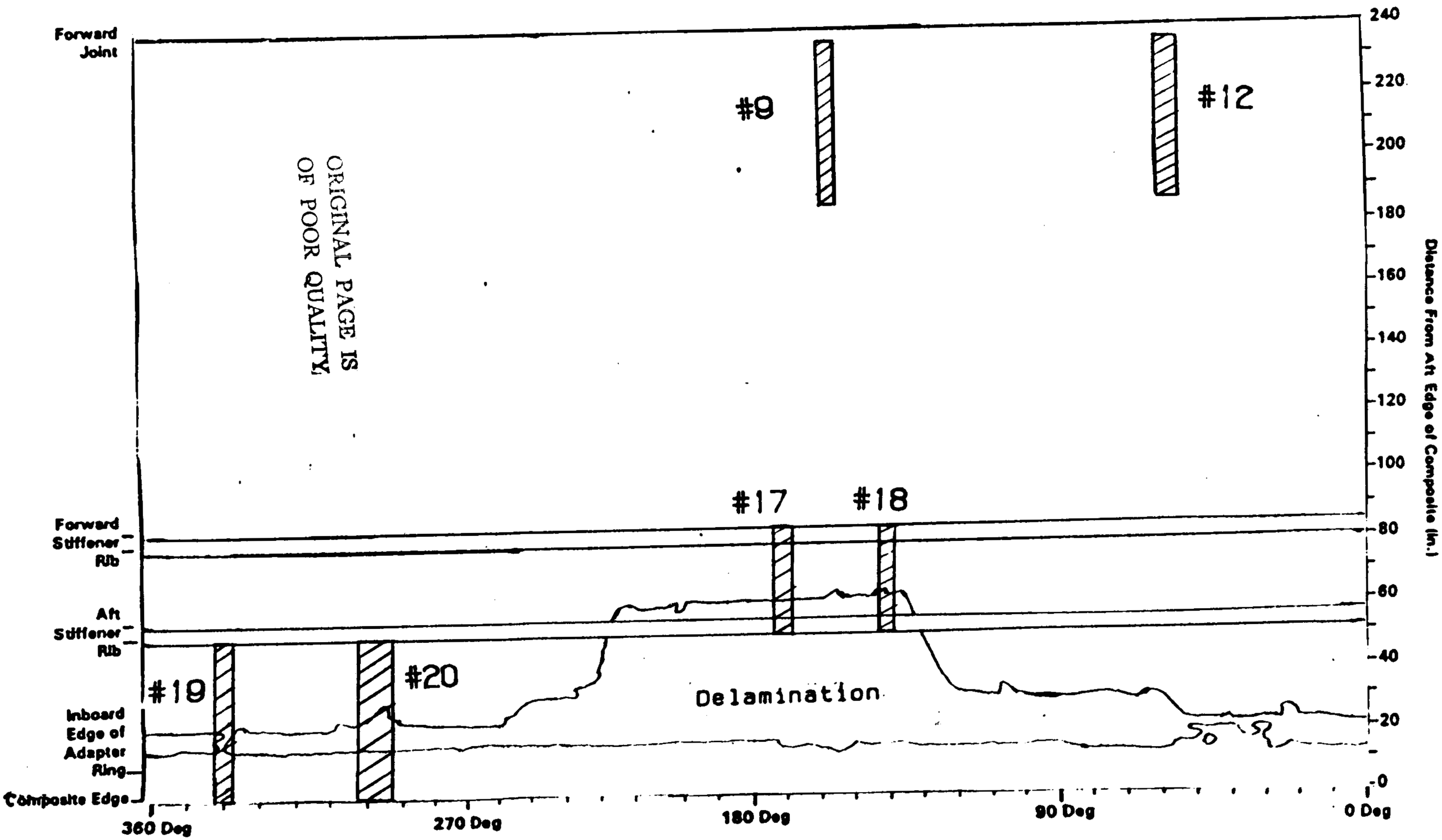

FIGURE 56. SAMPLE #9

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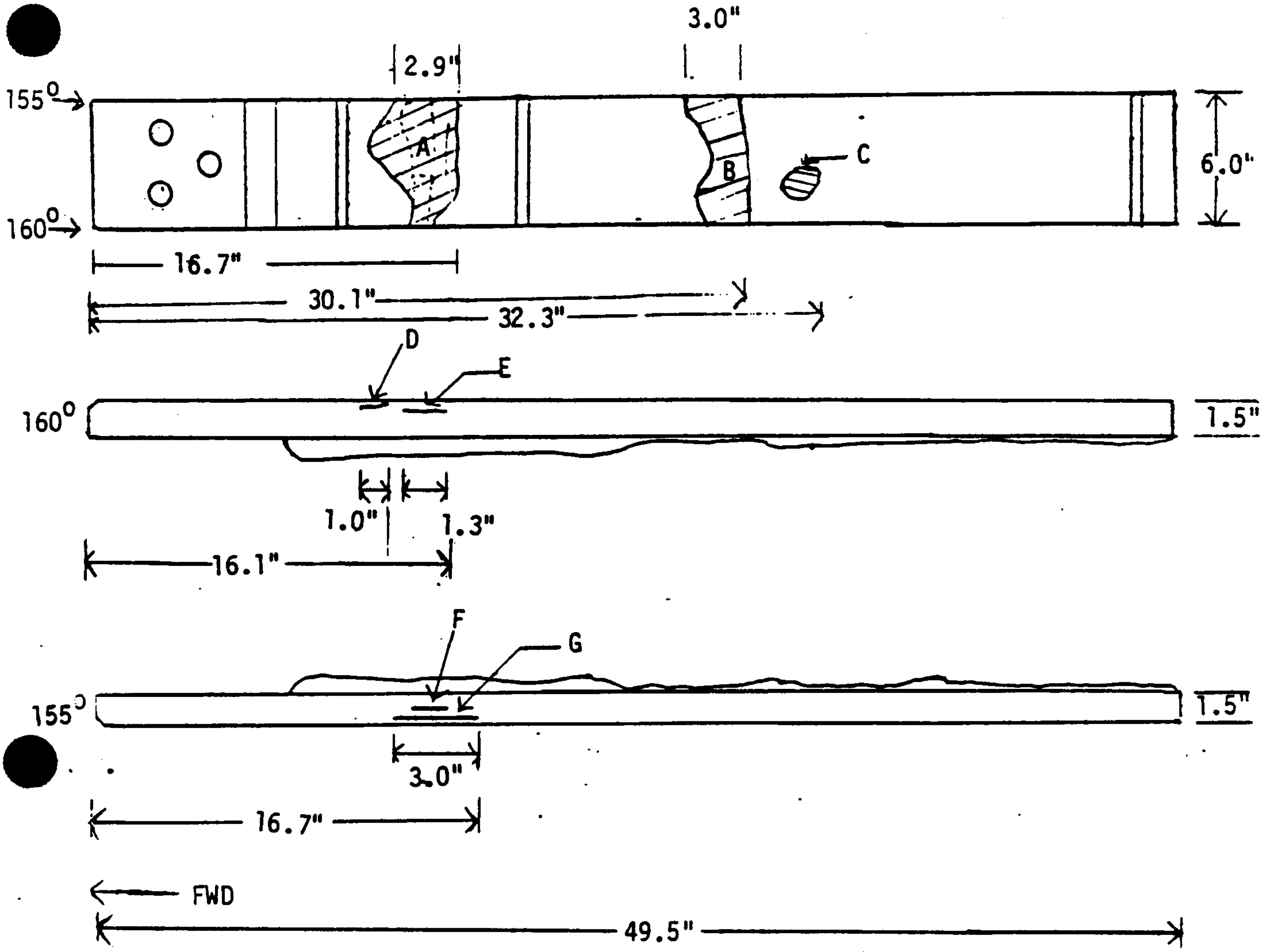


A. UT depth .080" - .120"
   Plastilock depth .080" scalar.

B. UT depth .060" - .075" thick plastilock layer at approximately .080" depth scalar.

C. UT depth .312"; diameter 1.5".

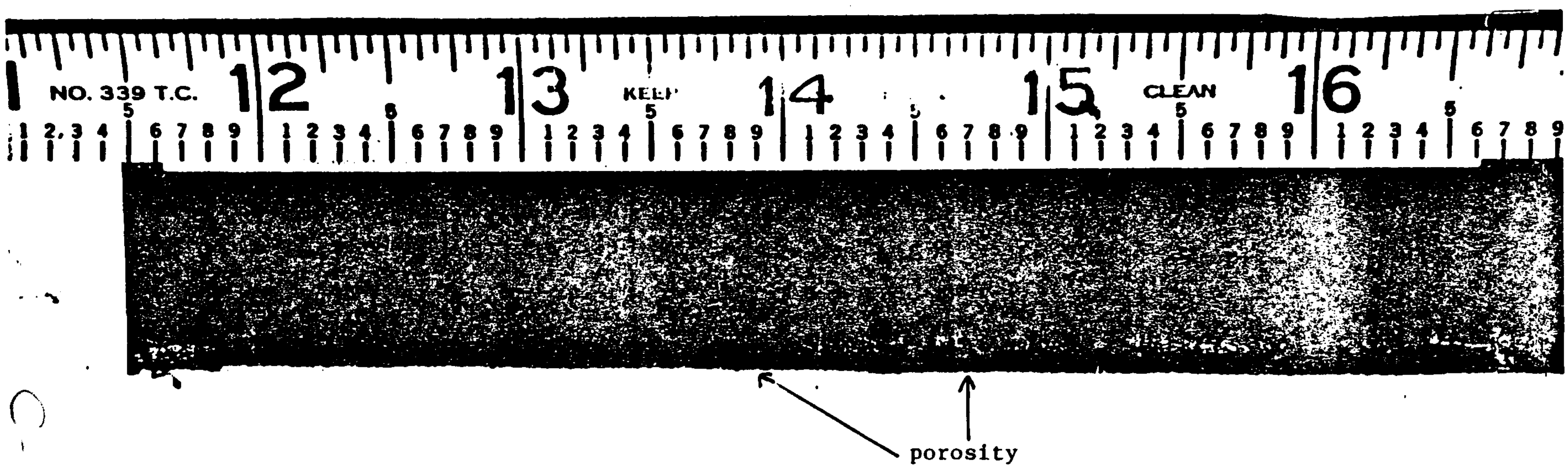
D. Visual delam from .085" - .185" cracks across plastilock into ply below. (scalar)

E. Visual delam from .247" - .290" (sloping ply) scalar.

F. Visual delam .247" scalar.

G. Sloppy plastilock (porous) at .100" scalar.

FIGURE 57. SAMPLE #9



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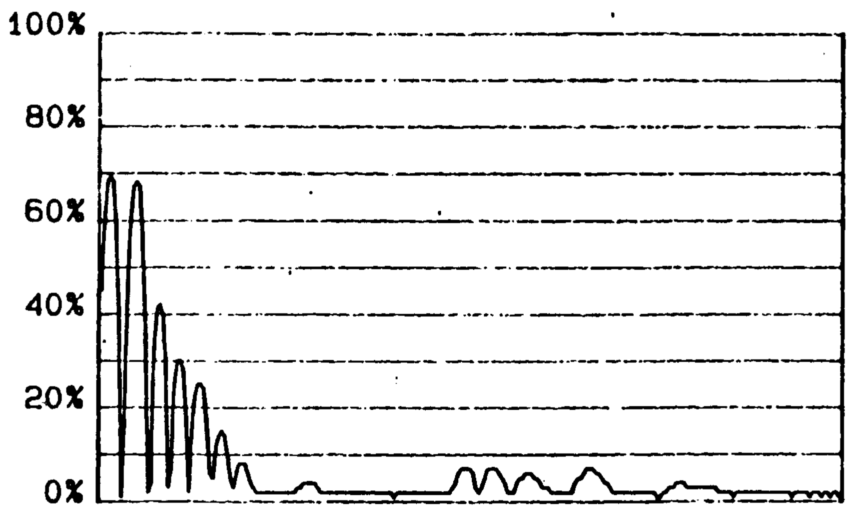
C-2

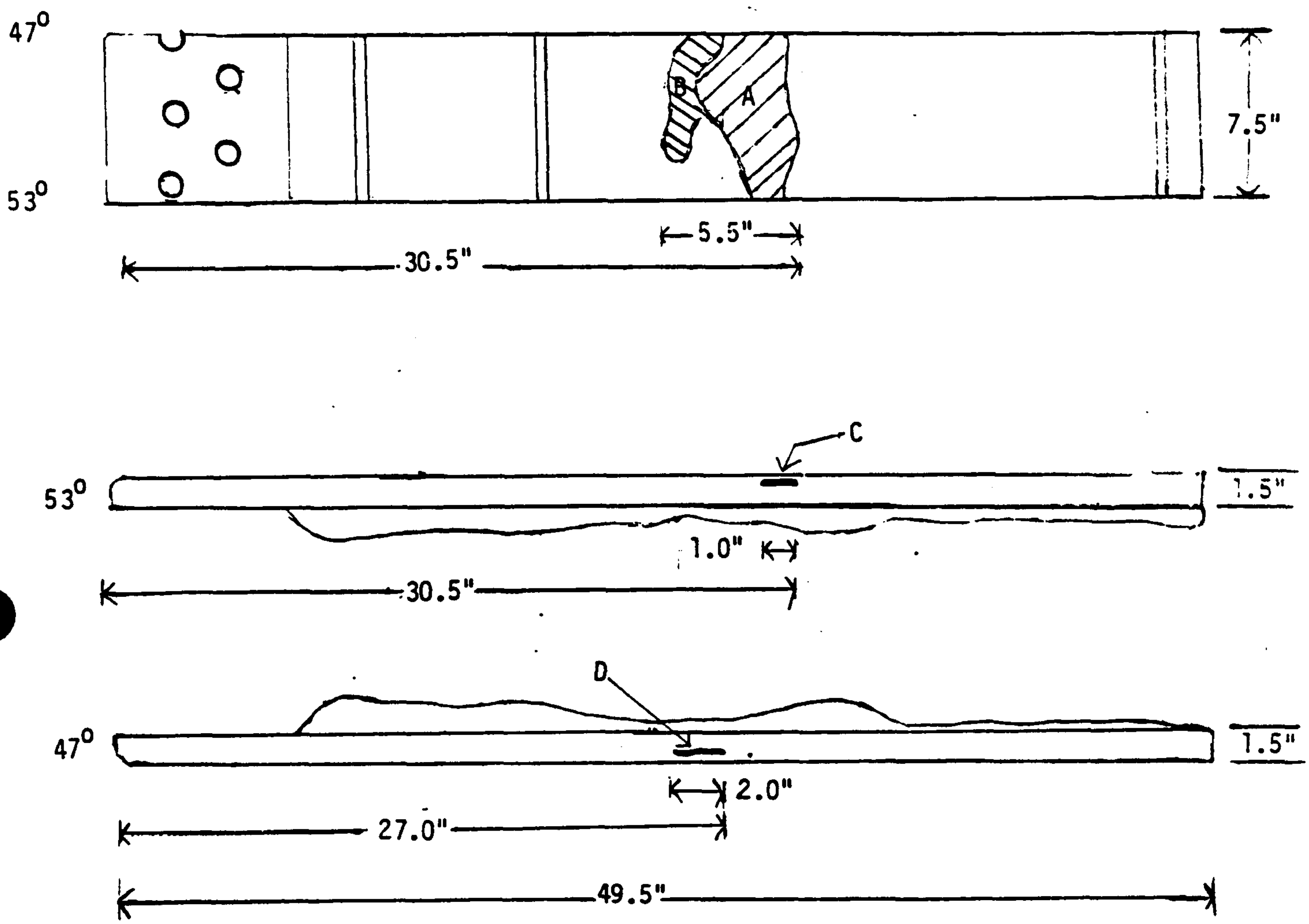
FIGURE 58.

MORTON THIOKOL INC



PART NO. STA-2A
S/N Sample #9
TECHNICIAN
TEST REQ Full-Wave
TEST LOCATION Area A

FIGURE 59. SAMPLE #12



A. UT depth .074"

B. UT depth .260"

C. Mechanical depth .076"

D. Mechanical depth .230" - .245"

FIGURE 60. SAMPLE #12

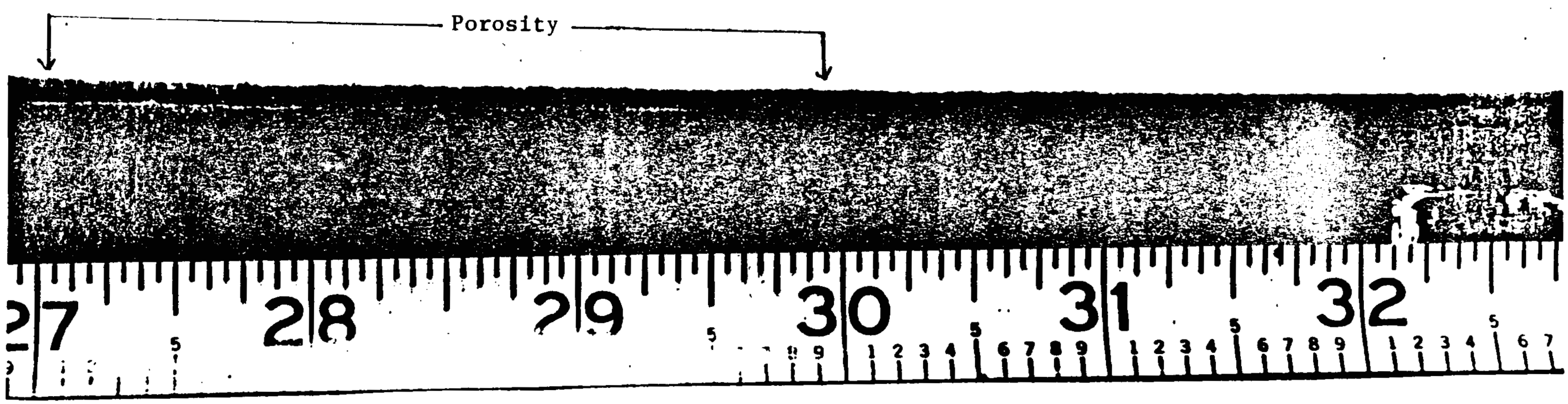
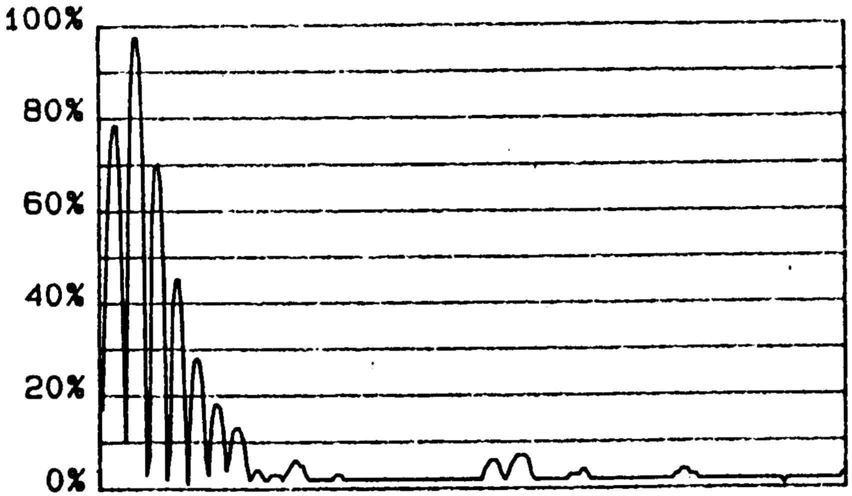


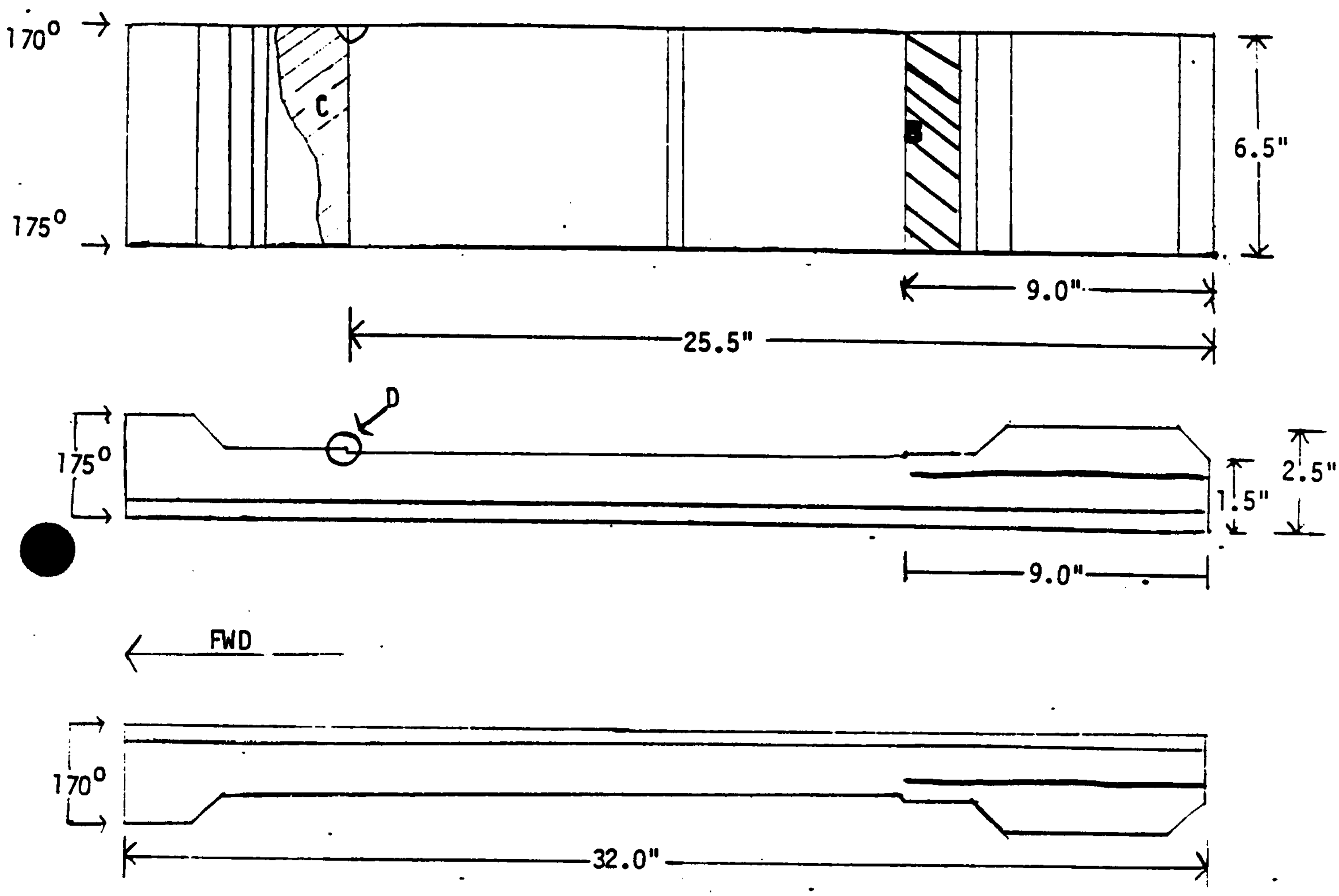
FIGURE 61.

MORTON THIOKOL INC



PART NO. STA-2A
S/N Sample #12
TECHNICIAN
TEST REQ Full Wave
TEST LOCATION Area B

FIGURE 62. SAMPLE #17



A. Visible delam: depth mechanical 1.480" (O.D.) UT depth 1.300"

B. UT depth .530" - .547".

C. High UT signal over 100% S.H. in center at .065" depth.

FIGURE 63. SAMPLE #17

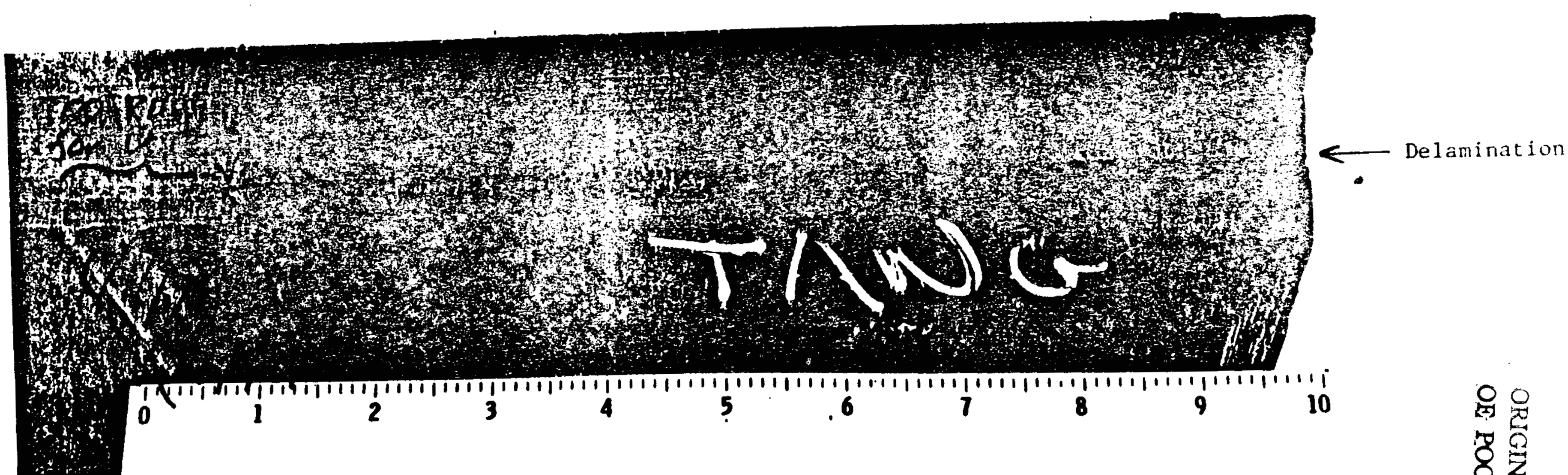


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FIGURE 64.

MORTON THIOKOL INC

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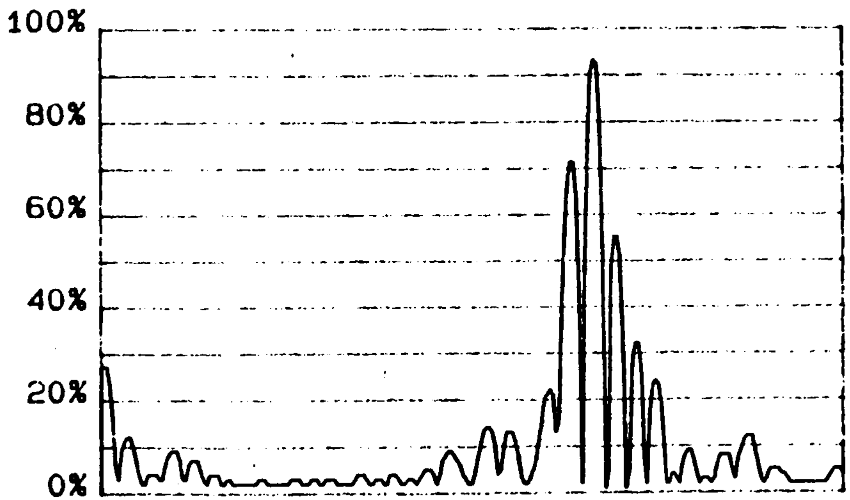


PART NO. STA-2A

S/N Sample #17

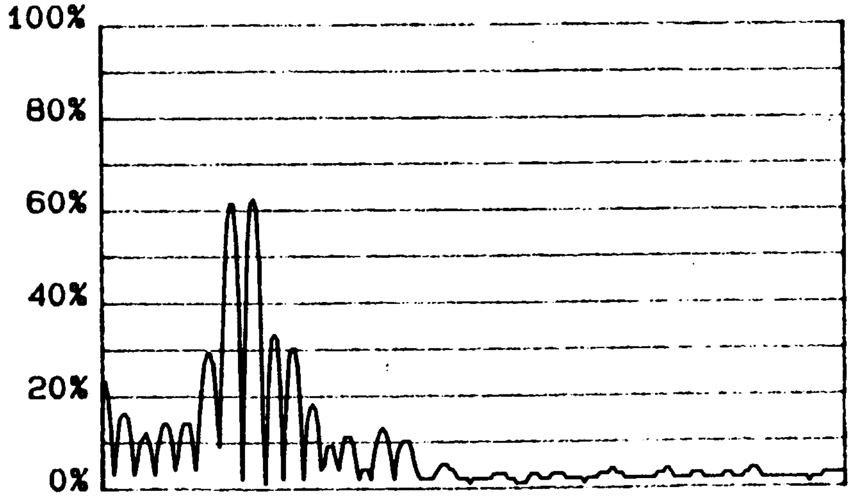
TECHNICIAN

TEST REQ Full-Wave

TEST LOCATION A

FIGURE 65.

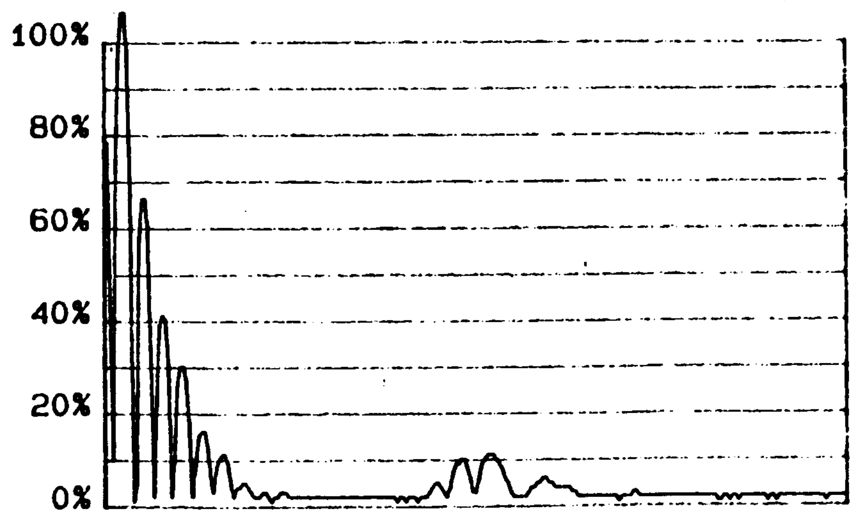
MORTON THIOKOL INC



PART NO. STA-2A
S/N Sample 17
TECHNICIAN
TEST REQ Full-Wave
TEST LOCATION B

FIGURE 66.

MORTON THIOKOL INC



PART NO. STA-2A
S/N Sample 17
TECHNICIAN
TEST REQ. Full-wave
TEST LOCATION C

FIGURE 67. SAMPLE #18

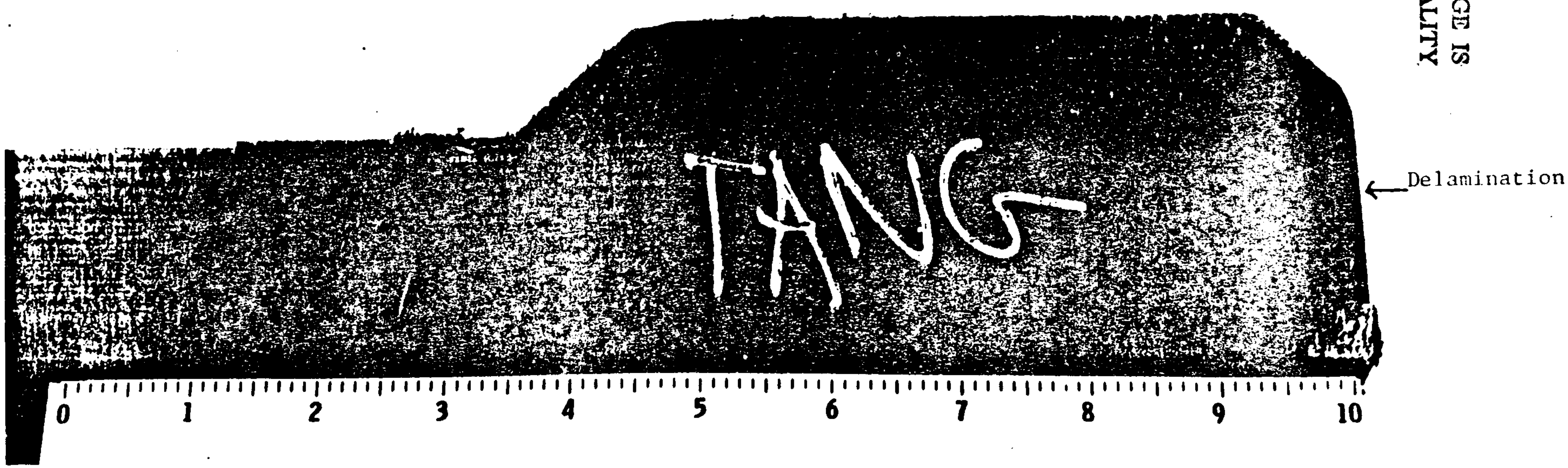
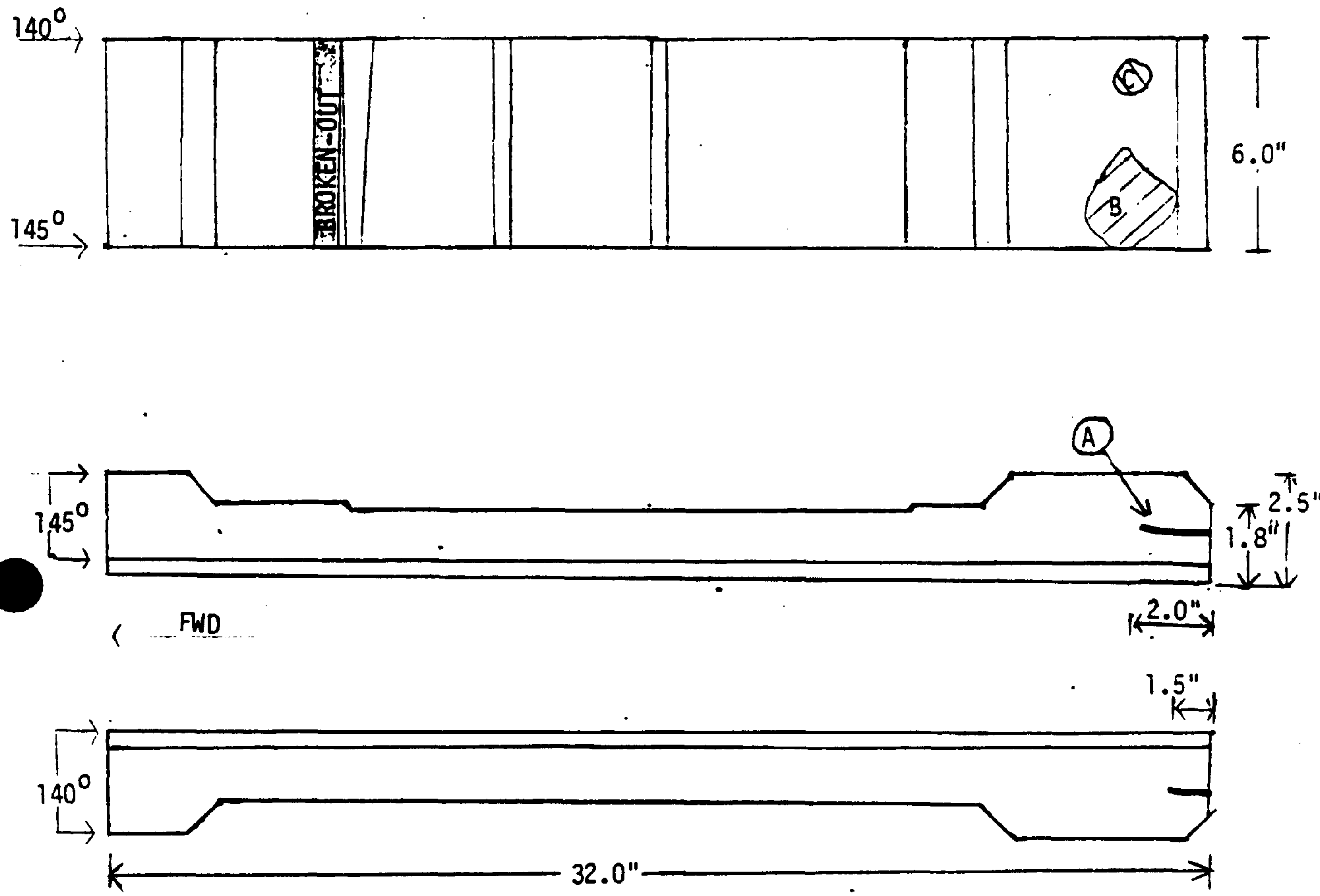


FIGURE 68. SAMPLE #18



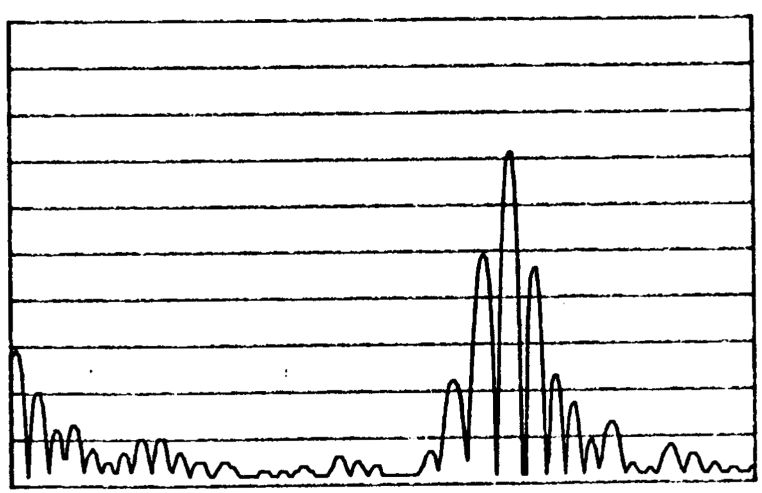
A. Scalar depth 1.515" from OD surface of Stiffener Rib.
Approx. scalar depth from OD cylinder .450". (ie - less Stiffener Rib).

B. UT depth 1.715" (75% S/H).

C. Small delam depth UT 1.734"

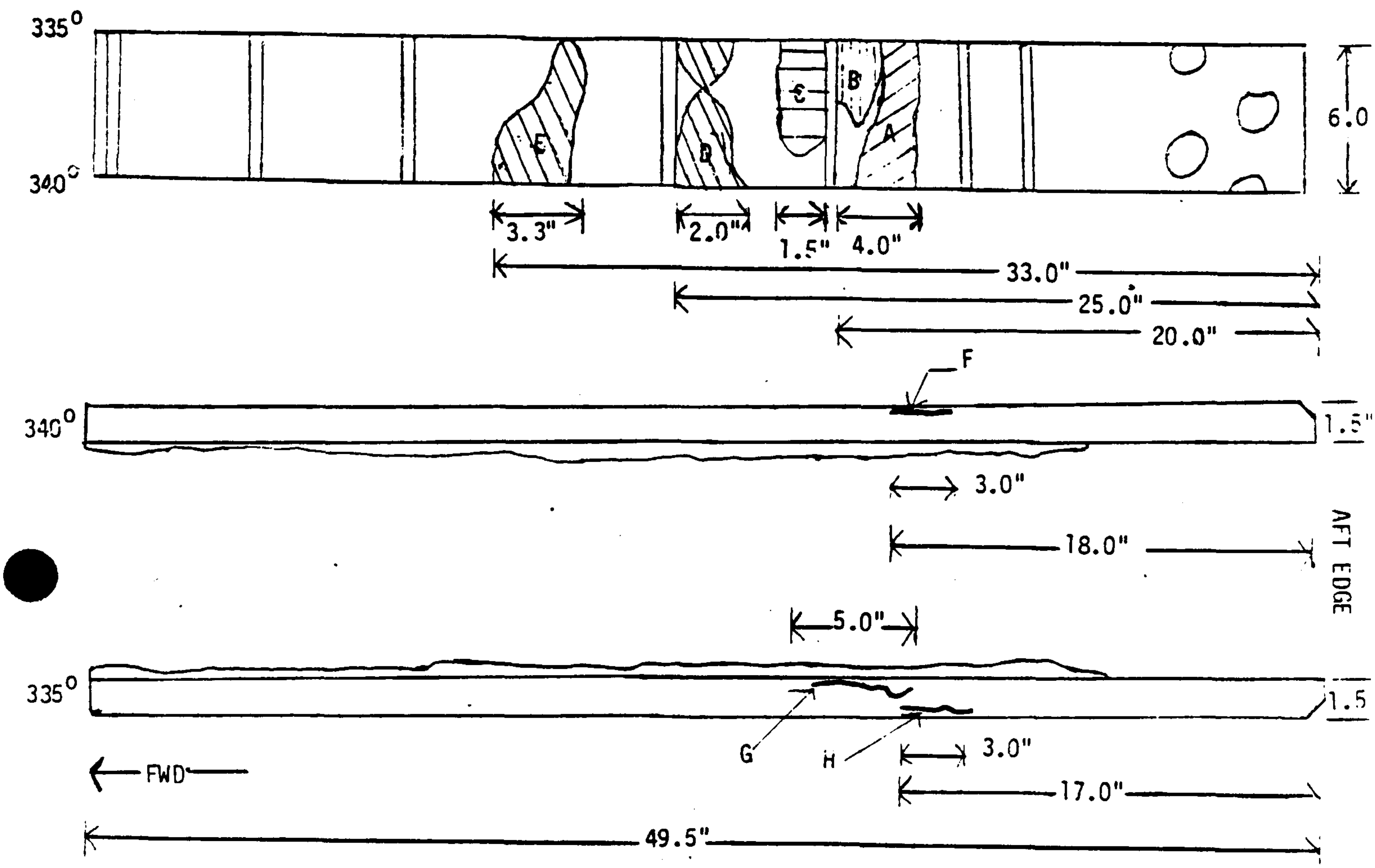
FIGURE 69.

MORTON THIOKOL INC



PART NO. STA-2A
S/N Sample #13
TECHNICIAN
TEST REQ Full-Wave
TEST LOCATION Area B
86-JUL-16FRAME NO : 13 SER

FIGURE 70. SAMPLE #19



A. UT depths .100" - .110" (porous plastilock)

C. UT depths .100" - .110" (porous plastilock)

B. UT depths .120"

E. UT depths .080" - .090"

F. Scalar depths .270" - .320"

G. 1.185" at 16.5 inches; 1.530" at 20 inches; 1.275" at 21.5 inches (scalar)

H. Cross-ply cracking from .095" at 14 inches (plastilock) to .340" at 17 inches (scalar).

FIGURE 71. SAMPLE #19

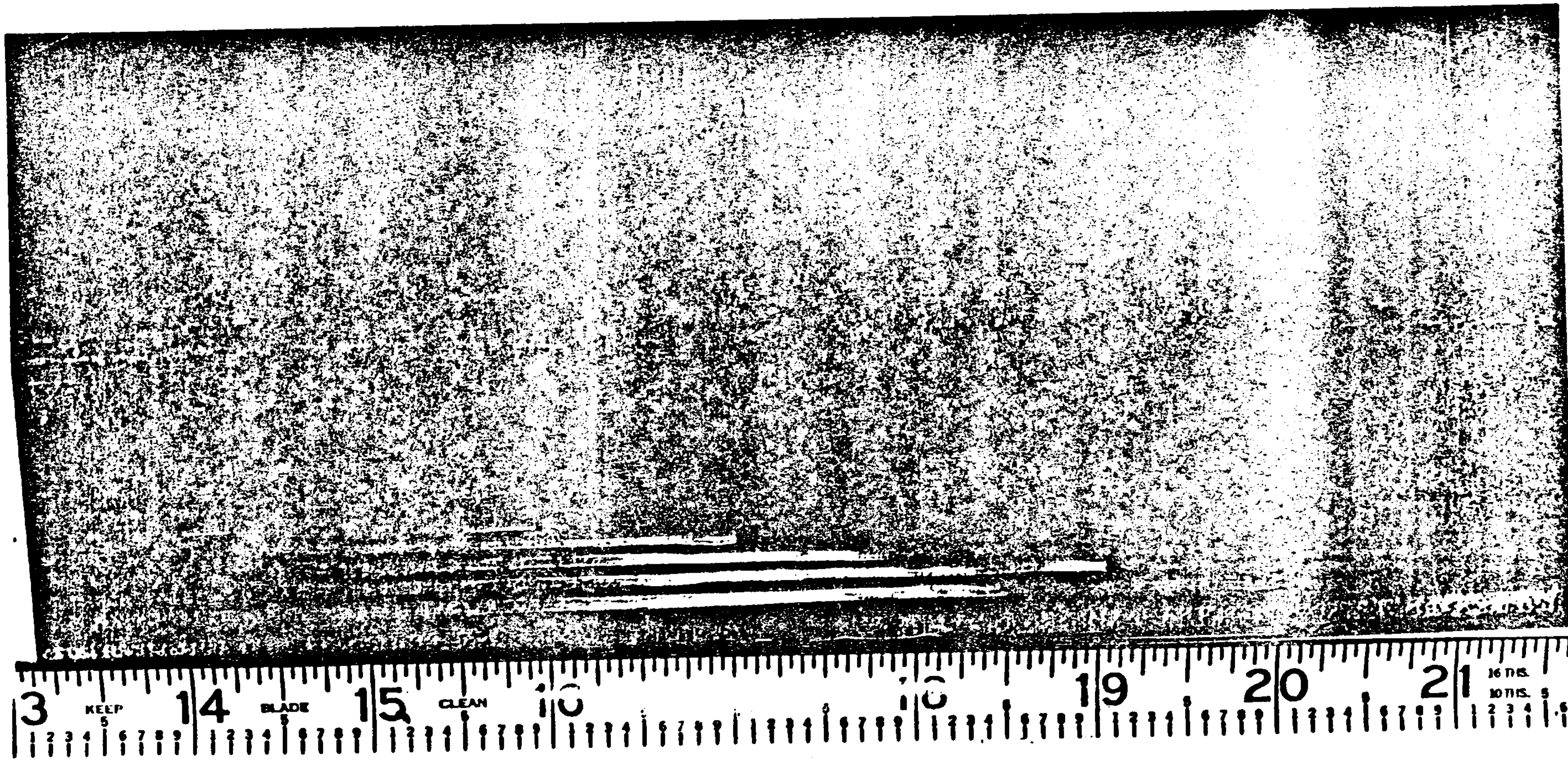


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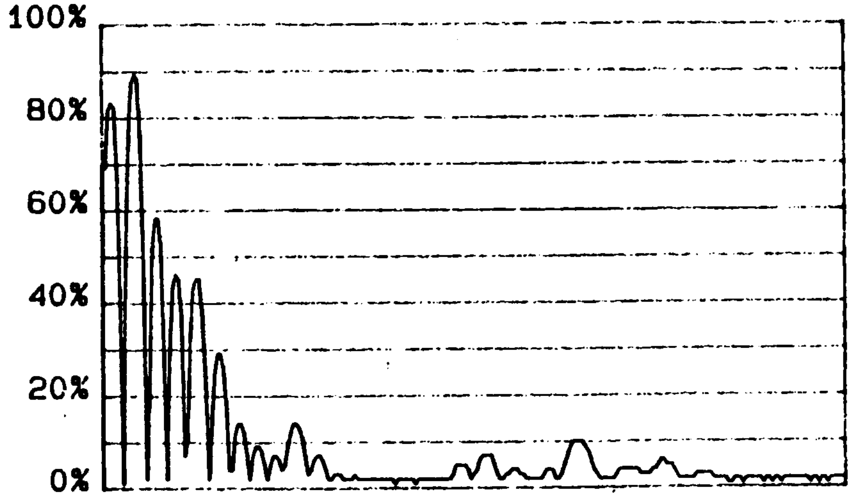
FIGURE 72.

MORTON THIOKOL INC



PART NO. STA-2A
S/N Sample 19
TECHNICIAN
TEST REQ Full-Wave
TEST LOCATION A

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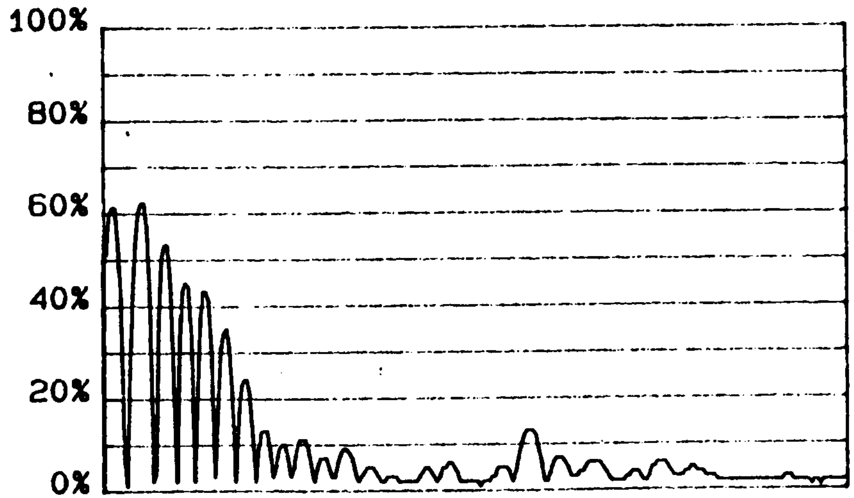
FIGURE 73.



PART NO. STA-2A
S/N. Sample 19
TECHNICIAN
TEST REQ Full-Wave
TEST LOCATION B

FIGURE 74. SAMPLE #20

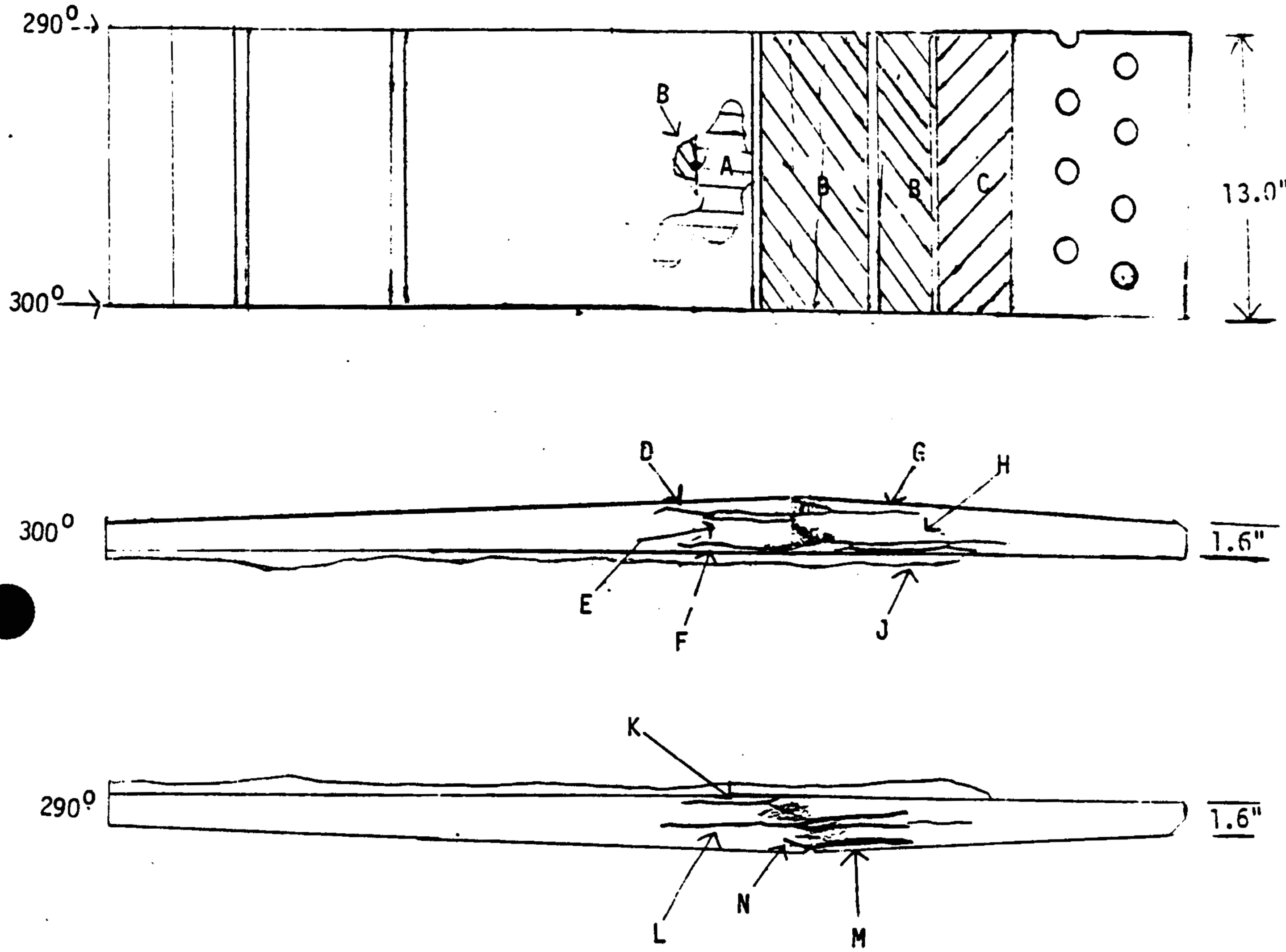


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FIGURE 75. SAMPLE #20

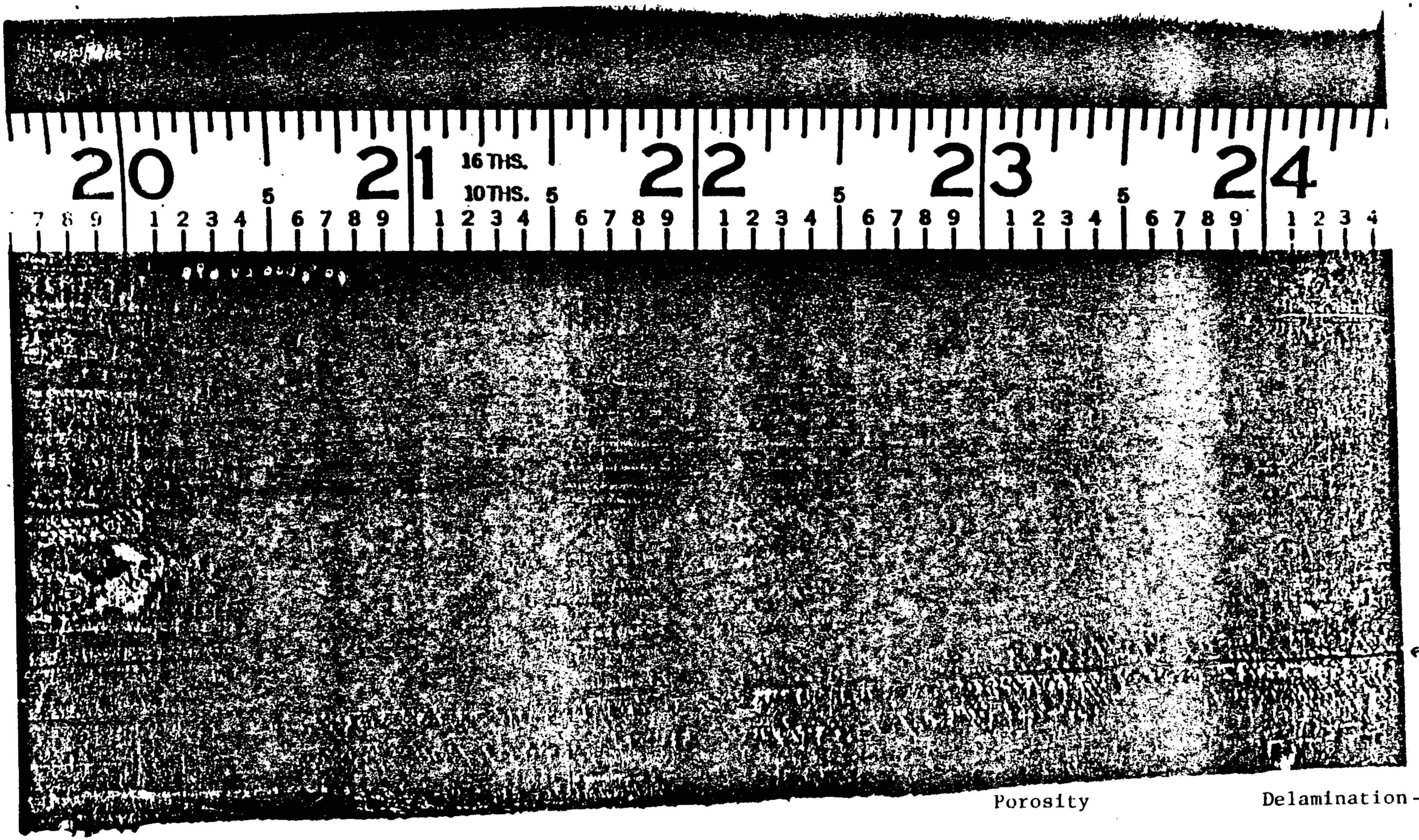
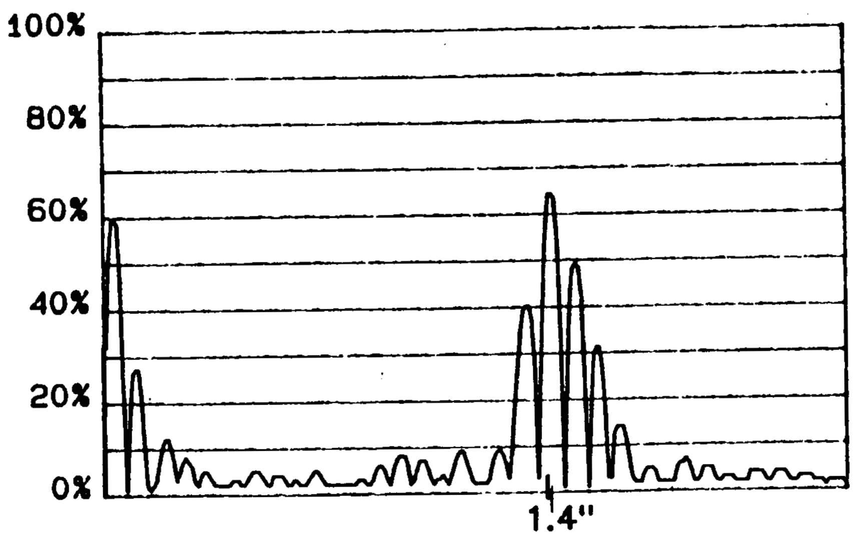


FIGURE 76.

MORTON THIOKOL INC



PART NO. STA-2A
S/N Sample #20
TECHNICIAN
TEST REG Full-Wave
TEST LOCATION C

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